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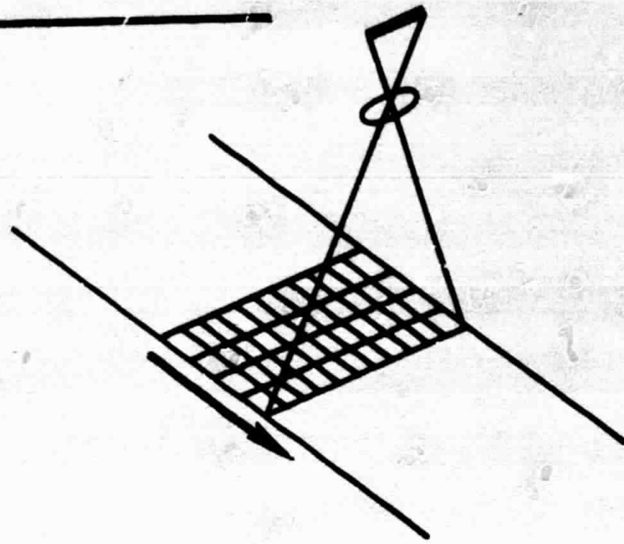

MRS

LITERATURE SURVEY OF BIDIRECTIONAL REFLECTANCE

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(NASA-CR-166669) MULTISPECTRAL RESOURCE SAMPLER: PROOF OF CONCEPT. LITERATURE SURVEY OF BIDIRECTIONAL REFLECTANCE (Operations Research, Inc.) 202 p HC A10/MF A01 CSCL 20F G3/43

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MULTISPECTRAL RESOURCE SAMPLER

"PROOF OF CONCEPT"

LITERATURE SURVEY OF
BIDIRECTIONAL REFLECTANCE

PREPARED FOR

NATIONAL AERONAUTICS & SPACE ADMINISTRATION

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND 20771

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I. INTRODUCTION

The Multispectral Resource Sampler "Proof-of-Concept" Study is intended to be a comprehensive analysis of the corrections that must be applied to MRS data to allow for atmospheric correction factors and the variability of bidirectional reflectance from the scene.

In order to assess the present state-of-the-art in these areas a literature review and analysis was initiated at the outset of the study. The reviews and analyses which are included have been compiled by:

DR. James A. Smith .... BIDIRECTIONAL REFLECTANCE
MR. Kenneth J. Ranson .... BIDIRECTIONAL REFLECTANCE

DR. Philip N. Slater .... ATMOSPHERIC CORRECTIONS
DR. Robert A. Schowengerdt .... ATMOSPHERIC CORRECTIONS

Their efforts include short descriptions of the more pertinent papers and bibliographies of the materials which have been reviewed.

The two Literature Surveys, Bidirectional Reflectance and Atmospheric Corrections, have been published under separate covers for ease of reference.

II BIDIRECTIONAL REFLECTANCE STUDIES

LITERATURE REVIEW

October, 1979

PREPARED BY: Dr. J. A. Smith and
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2.0 INTRODUCTION

The present bibliography was compiled in order to present a fairly comprehensive review of previous work in scene bidirectional reflectance, particularly those studies relevant to the Multispectral Resource Sampler (MRS)(Schnetzler and Thompson, 1979). The literature review has been prepared in two parts. Part I, reported here, is a bibliography of the pertinent references. It was found convenient to organize the selected references into four broad categories: 2.1 Theory and Models, 2.2 Measurements - further broken down into laboratory, field and platform, 2.3 Applications and Techniques, and 2.4 Definitions. First, an overview of the references contained in each section is given. Then an alphabetical list of the references by section and, finally, the individual citations with abstracts are included.

Part II, is a synthesis of the literature results in narrative form.

The Multispectral Resource Sampler (MRS) is a proposed sensor system, operating in the 0.36 to 1.0 micrometer region, to be flown by the National Aeronautics and Space Administration in the mid 1980's. The MRS is to be a pointable sensor with across track pointing up to $\pm$ 40° and along track pointing up to 55°. The proposed data acquisition needs and satellite trajectories will also result in the imaging of scenes under a range of sun angles. It is thus important to determine the angular reflectance characteristics of natural targets as summarized in the bidirectional reflectance distribution function, BRDF. If the BRDF exhibits significant anisotropy, then correction procedures must be investigated in order to utilize multitemporal data sets imaged under different view or illumination angles. Similarly, it is of interest to

determine if new channels of information are provided by a knowledge of the angular distribution of reflected energy.

In order to fully document the relevant surface anisotropy effects on a sensor such as the MRS, one must also consider the intervening atmospheric effects. However, a separate literature review study focusing on these effects is being prepared by other investigators. Consequently, articles dealing primarily with the atmospheric processes have been omitted from this report. Further, the bibliography includes only those references dealing with directional scattering properties of natural targets.

The references reported here were obtained from a computerized retrieval search through NTIS and other sources, as well as from the authors' own literature collection. We believe the list is fairly comprehensive, but not necessarily exhaustive. Remote sensing is a rapidly evolving field. As in all literature reviews, a cutoff date had to be imposed. Thus, very recent symposia, for example the Thirteenth International Symposium on Remote Sensing of Environment and the 1979 Symposium of Machine Processing of Remotely Sensed Data are not included. In general, articles beyond May 1979 were not reviewed.

There appear to be an abundance of measurements of directional reflectance properties of natural materials, Section III. However, there is considerable confusion and variability in the interpretation of the measurements and experimental procedures. The references in Section IV help explain the preponderance of terms and conceptions in the literature. The experimental situation is also often obscured by the lack of backup documentation of the materials studied. Several theories of canopy reflectance have been developed, Section I. The

theoretical foundation for infinite plane-terrain models appears strong. Further extension of these techniques to heterogeneous canopies is required. The possible utilization of the directional scattering properties of natural materials for increased information extraction has only recently been addressed, Section III. Primarily, this appears to be a result of the experimental difficulties in registering aircraft multispectral data and accounting for atmospheric variability during flight acquisition times. The reflectance models predict increased biomass discrimination given off-angle measurements. The advent of sensor systems such as the MRS which provide a stable platform and rapid acquisition times warrants further research in this area.

Schnetzler, C.C. and L.T. Thompson. 1979. Multispectral Resource Sampler: An Experimental Sensor for the Mid-1980's. Proc. SPIE Tech. Symp., Huntsville, AL May 22-24, Vol. 183. 8 p.

2.1 THEORY AND MODELS

We have identified 45 references which are concerned with radiative transfer calculations in the optical regime and oriented towards a remote sensing perspective. We have not included any of the numerous references dealing with light interception as applied to photosynthesis studies. The references may be grouped naturally into three general areas: (1) Canopy Reflectance Modeling, (2) General Radiative Transfer Theory, and (3) Application of Radiative Transfer Theory to measurement interpretation.

Approximately 30 of the references deal with canopy modeling. However, upon closer examination we find that only a few investigators have actually concerned themselves with this problem. There is the classic work of Allen and Richardson (1968), Allen, Gayle, and Richardson (1970), and Duntley (1942, 1969). Allen and Richardson were among the first investigators to apply physically based radiative transfer theory to vegetation canopies. Allen, Gayle and Richardson demonstrated that the Duntley equations could be interpreted to include effects of sun angle on plant canopy. Thus, they are able to explain diurnal reflectance versus sun angle. Recently, other investigators also with the U.S. Department of Agriculture, primarily Idso and deWit (1970) and Jackson *et al.* (1979) have initiated new model development. The reference by Jackson *et al.* is given in the section on Applications and Techniques, Section III.

Canopy model studies are currently dominated by two strong schools of thought. The first of these is exemplified by the Suits (1972) model. Nine of the references explain the development of this model and the application of the model by various scientists. Also included are

analyses of the model by Chance and LeMaster (1977) at Pan American University. The Suits model represented an advancement over the earlier work of Allen and Richardson, in that it allowed the stratification of a canopy into layers. It is a deterministic model which utilizes the radiative transfer equations directly. The second major thrust in canopy modeling was initiated by Smith and co-workers (1972) at Colorado State University. Five of the references are spinoffs from this work. The SRVC (Solar Radiation Vegetation Canopy) model is a Monte Carlo model which simulates light interaction with the various layers of a vegetation canopy. Both the Suits and SRVC models are infinite plane terrain models which predict bidirectional reflectance properties of the canopy as a function of intrinsic canopy characteristics.

A major effort in canopy modeling studies also appears to have been undertaken by the Dutch, principally Bunnik (1978) at NIWARS. Other investigators include Goudriaan (1977) and Verhoef and Bunnik (1975,1976). The paper by Bunnik is particularly significant.

Finally, in the model studies area there are a number of other investigators which contribute four of the references. Norman (1979), currently at the University of Nebraska, has undertaken recent work on the application of radiatve transfer theory to non-homogeneous canopies. The reference by Ross (1976) is an entree to the Russian literature which is quite extensive. In this category it should also be mentioned that an important effort was undertaken by Egbert (1977) and Ulaby at the University of Kansas. The reference by Egbert is given in the section on Applications and Techniques. However, no further model development or application appears to have been continued by the Kansas group.

The second category of references in this section deal with general radiative transfer theory, although not necessarily applied to natural scenes. The classic texts of Chandrasekhar (1960) and Preisendorfer (1965) are fundamental to the field. The review article by Ishimaru (1977) is comphrehensive. The article by Leader (1971) is significant.

Finally, five of the references deal with the application of radiative theory as required to understand or interpret measurements. Two of the investigators deserve to be highlighted. Kriebel, et al. (1976) demonstrate that the determination of the bidirectional reflectance distribution function requires a knowledge of the sky radiation and path radiance terms. He outlines an iterative procedure for solving the combined atmospheric/scene radiative transfer system. Other references by Kriebel are given in the section on Measurements, Section 2.2. The work by Egan dealing with polarization properties of surfaces should be noted. Again, other references by Egan are given in Section 2.2.

In summary, a solid, but recent, body of knowledge exists for the calculation of the bidirectional reflectance distribution function for some plant canopies. Principally, these include crops, rangeland, and grasses which have a uniform cover and large areal extent. The Suits and Smith models have also been applied to forest canopies. The models are not as well developed to handle heterogeneous situations such as crops with significant row structure. However, these areas are now being investigated. Considerable ground control information concerning canopy structure is required to drive the models.

2.2 MEASUREMENTS

We have broken down the references in the measurements section according to whether they were primarily made in the laboratory, in the field, or from a platform such as aircraft or satellite. The separation of the references into these three categories is not always unique. Many investigators will gather both field and aircraft measurements, for example. Further, many experimenters will incorporate a significant amount of theory to interpret their measurements. Nevertheless, the breakdown appears to be a workable modus operandi.

A. LABORATORY

Most of the Laboratory references we have selected are from the 1970's with the exception of the early work by Coulson (1965, 1966) and Gates, et al. (1965). One would think that there would be hundreds of references dealing with laboratory measurements of scattering properties from natural target materials. As a matter of fact, this does not appear to be the case. Perhaps, the remote sensing field is so indoctrinated with the concept that things appear differently in the field under natural illumination than in the laboratory under artificial conditions, that many investigators question the value of laboratory measurements. As pointed out by some of the references in the section on field measurements, there is still a need to gather further laboratory measurements under controlled and known illumination.

Under laboratory measurements, the classic work of Coulson must clearly be highlighted. Coulson performed several measurements of directional reflectance or hemispherical conical reflectance of natural surfaces. These surfaces included soils, clays, quartz, and some vegetation. Visible and near-IR measurements, as well as polarization analyses, were performed.

Coulson also made measurements in the field as indicated in the next section. Other early references include Gates, et al. (1965) and Hapke and Van Horn (1963).

The paper by Breece and Holmes (1971) is very significant in that it is the only paper the authors could uncover that performed detailed bidirectional scattering measurements of component foliage elements. The work was carefully executed and gives the directional distributions for both transmission and reflectance. As the canopy reflectance models, referred to in Section I, become more sophisticated, these types of measurements will become essential. Further work needs to be done in this area; however, no one seems to have continued along this avenue.

The references by Egan (1968, 1970) include bidirectional photometry and polarization studies of crops and soils. As with other investigators, Egan points out the highly dependent nature of reflectance with view angle.

Finally, the continuing research of Graham Hunt and coworkers (1976) at the U. S. Geological Survey dealing with laboratory measurements of geologic materials should be noted.

B. FIELD

Probably, the most significant source for field measurements is the work emanating from the Large Area Crop Inventory Experiment (1978). This material is archived at LARS (Bauer, et al., 1977, 1978). There is heavy emphasis on wheat, although other crops are also included. Most of the measurements were taken under a nadir looking view angle. However, variable sun angle and phenology are included. Further, there is good supporting ancillary data.

Again, the work by Coulson and Reynolds (1971) contains reflectance

information versus solar elevation for soils, asphalt, alfalfa, rice, sugar beets, bluegrass, and sorghum. Other sources of albedo values include the Target Signatures Library of the Willow Run Laboratories, now ERIM, (Earing and Smith, 1964). The Russian work by Kondratiev, et al. (1964; Steiner and Cuterman, 1966) contain good albedo references for a wide variety of materials.

Other agricultural reflectance data are available in Verhoef and Bunnik (1976), de Boer, et al. (1974), Kanemasu (1974), and the recent paper by Rao, Brach, and Mack (1979). This latter paper contains information on the angular effects versus leaf area index and percent ground cover. The data were corrected for view angle, solar zenith and azimuth angles, and atmospheric effects. Information is given for barley, oats, and corn.

The references by Duggin (1977), Egbert and Ulaby (1972), and Smith, Berry, and Heimes (1975) contain further information on directional variability in crop signatures. The references by Tucker (1979) contain information on various ratio variables versus agricultural parameters.

Field measurements for the directional reflectance of various types of snow using artificial light were obtained by Middleton and Knowles (1952). Snow appears to exhibit large increases in reflectance for large angles of incidence and reflection. The reference by Dirmhirn and Eaton (1975) is a more recent reference summarizng diurnal variations of albedo for snow and ice. Freshly fallen snow is found to be highly isotropic, with specular components increasing with age.

The reference by Fuller and Rouse (1979) is interesting for the lack of understanding exhibited in terms of the meaning of a reflectance parameter. They noted changes in reflectance for overcast versus clear skies with the directional component of reflected flux being small under overcast skies. They indicate that an overcast sky decreased the albedo

at large zenith angles for forest canopies. The authors clearly do not understand the coupling between the irradiance field and the bidirectional reflectance factor as explained in the references in Section 2.4. Definitions. The reference by Kimes, Smith, and Ranson (1979) is a good overall summary of this coupling and the interpretation of vegetation reflectance measurements as a function of solar zenith angle.

C. PLATFORM (AIRCRAFT AND SATELLITE)

While aircraft and satellite multispectral scanners have been flown for several years, really few studies have been devoted to the use of these systems for estimating surface reflectance properties. Rather, pattern recognition and other classification approaches are performed directly on the radiance measurements themselves to extract the information desired. Under this category, however, we again find the ever present Coulson (1966). This reference contains measurements of reflecting and polarizing properties of various soils, sands, and vegetation in the visible and near-IR spectral regions. Coulson found that dark surfaces polarize reflecting radiation most strongly while highly reflecting surfaces have relatively weak polarizing properties.

Probably, some of the most significant aircraft measurements that have been obtained and analyzed are those by Kriebel (1974, 1976, 1978). Kriebel made a complete analysis involving both atmospheric and sensor considerations to derive a true bidirectional reflectance distribution function for four broad vegetation categories. These include bog, pasture, forest, and crops. The information available is very relevant to bidirectional reflectance studies and the MRS. However, it is apparent that some numerical inversion errors accumulated in the analysis. The tabular data do not always satisfy the reciprocity relationship. The data

are averaged over solid angles of 30 degrees azimuth and 10 degrees zenith angle. For all surfaces, anisotropy increases with increasing zenith angle of incidence, apparently due to the shadowing effects in the vertical canopy structure.

The data given by Salomonson (1966) and Salomonson and Marlatt (1968, 1971) indicate anisotropy over various surface materials. For example, backscattering predominates over grassland surfaces at large solar zenith angle. The ratio of average observed reflectance to the minimum observed reflectance varied from 1.09 to 1.40. Measurements over vegetation, soils, snow, and white gypsum sand are given.

The references by Duggin (1974), Hoffer (1974), and Smith, Lin, and Ranson (1979) contain useful information for the documentation of the anisotropy to be expected for satellite measurements.

2.3 APPLICATIONS AND TECHNIQUES

Under this section we include references dealing with correction procedures for removing variations induced by bidirectional reflectance effects, principally scan angle and sun angle, and papers which examine possible applications of the BRDF differences in scene elements.

In reviewing the literature for correction techniques related to BRDF effects, it is apparent that the most commonly employed method is to avoid the problem. That is, most analyses of multispectral aircraft data usually include only restricted flight times, near solar noon, and restricted scan angles. The Environmental Research Institute of Michigan, which has had considerable experience in the acquisition and analysis of aircraft MSS data, is a good source for correction procedures. The report by Nalepka and Erickson (1974) presents a summary of a five-year research program dealing with the application of MSS systems to earth resource surveys. Egbert (1977) presents a novel approach to correct bidirectional reflectance values. The analysis of BRDF effects on satellite imagery, principally Landsat, is given by Ranson, et al. (1978), Lambeck (1977), Holben and Justice (1979), and Struve, et al. (1977). Horn and Bachman (1978) applied surface response models to Landsat imagery in order to develop registration techniques.

Indirect BRDF effects are manifested in satellite data through multitemporal analyses. Kauth and Thomas (1976) present a unique summary of this problem by employed a "tasselled cap" transformation.

The influence of the BRDF surface effects on atmospheric corrections is summarized by Coulson and Jacobowitz (1972) and Koepke and Kriebel (1978).

In summary, correction of aircraft multispectral bidirectional reflectance effects is confounded by atmospheric effects as well as the surface anisotropy. Satellite bidirectional reflectance effects are confounded by the variability resulting from the large geographic extent imaged.

The number of investigators who have studied the potential application of surface BRDF variations for information extraction is limited. The report by Malila, Hieber, and Sarno (1974) describes an aircraft experiment in which the multispectral scanner was flown over the same flight line twice; first at 0 degree look angle, and then tilted at a 45 degree look angle. The images were manually registered. Some improvement was noted; however, the results were confounded by possible atmospheric variability and registration problems. The paper by Smith and Oliver (1974) presents a theoretical investigation of the BRDF effects on feature selection. Improvement at some combinations of sun/sensor angles is predicted for biomass mapping. This result is also indicated in the work by Bunnik (1978) given in Section 2.1. Finally, the paper by Jackson, et al. (1979) discusses an analytical approach for using the canopy bidirectional reflectance distribution function to estimate crop structure parameters.

2.4 BIDIRECTIONAL REFLECTANCE: DEFINITIONS

Even a casual review of the references given in the present bibliography demonstrates an almost overwhelming diversity of measurements approaches and interpretations for the "reflectance" of a scene. Three of the references included in this section highlight the reasons behind the apparent confusion in the literature. First is the classic reference by Judd (1967) who, in fact, defines nine kinds of reflectance, six kinds of reflectance factors, and three kinds of radiance factors. In particular, Judd uses the terms hemispherical, conical, and directional to specify both angles of incidence for the irradiance and angles of collection for the exitance. Judd does an excellent job of emphasizing the angular considerations and inter-relationships involved in reflectance nomenclature. However, the papers by Nicodemus (1970, 1965) present a summary of the important concept of the bidirectional reflectance distribution function, the BRDF. Nicodemus restricts the term reflectance to the dimensionless ratio of a reflected radiometric quantity, e.g. radiant power, to the corresponding incident radiometric quantity. This ratio is always less than or equal to one. The BRDF, a differential quantity, has units of sr^{-1}. The term reflectance factor is defined as the ratio of the radiant power, exitance, reflected by the scene to that which would be reflected by a perfect Lambertian surface. The incident and collection beam geometry are taken to be the same. The third fundamental reference, the Self-Study Manual on Optical Radiation (1978), edited by Nicodemus, is an excellent tutorial on radiance concepts and presents a measurement equation for radiometry. Finally, the paper by Kasten and Raschke (1974) is similar to the earlier papers by Nicodemus but is helpful as a reference for Kriebel's papers presented earlier.

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2.5.2 MEASUREMENTS

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2.5.4. BIDIRECTIONAL REFLECTANCE: DEFINITIONS

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2.6 REFERENCE LIST: BIDIRECTIONAL REFLECTANCE

I. DIRECTIONAL REFLECTANCE: THEORY AND MODELS

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IV. BIDIRECTIONAL REFLECTANCE: DEFINITIONS

7 References

I. DIRECTIONAL REFLECTANCE: THEORY AN'D MODELS

45 references

Allen, W.A. and A.J. Richardson. 1958. Interaction of Light with a Plant Canopy. J. Opt. Soc. Am. 58(6):1023-1028.

The Kubelka-Munk (K-M) theory has been applied to light interaction with leaves stacked in a laboratory spectrophotometer. The theory can also be applied to an actual field plant canopy. The K-M theory is a two-parameter generalization of the one-parameter Bouguer-Lambert, or Beer's law, relation. The older theory accounts for transmittance of a medium but not for reflectance. The K-M theory, however, yields a theoretical value both for reflectance and transmittance. The K-M theory is applied in this paper to the reflectance and transmittance of stacked mature cotton leaves over the spectral range 0.5-2.5 μ. The standard deviation between theory and experiment, after known biases are calculated and removed from the data, is about 1%—a discrepancy well within experimental error. A procedure is developed to apply the K-M theory to an actual plant canopy. The method involves regression analysis to light flux measurements within a plant canopy. Differential coefficients are derived for use in both stacked-leaf and canopy applications.

Allen, W.A. and A.J. Richardson. 1970. Plant-Canopy Irradiance Specified by the Duntlye Equations. Journal of the Optical Society of America 60(3):372-376.

The Duntley equations for propagation of unidirectionally incident light through a diffusing medium have been generalized and interpreted to account for the diurnal nature of near-infrared radiation measured in an Ithaca, N. Y. corn canopy. The Duntley optical coefficients associated with the specular component of light were assumed to vary as the secant of the sun's zenith angle. Generalization of the Duntley relations was required in order to predict values of irradiance within the canopy and to account for the effect of background reflectance from the soil. Five independent measurements of canopy irradiance suffice to determine the Duntley parameters. Twenty-four measurements of transmittance within the canopy were used, however, in a least-squares calculation to obtain the best fit of the Duntley equations to irradiance within the corn canopy. The Duntley equations fit the experimental results within a standard deviation of 3.2% for a period from noon to sundown. If the laboratory measurements of optical constants for a single corn leaf are used as constraints, the Duntley equations fit the data to within 3.7%. The best fit to near-ir transmittance measurements occurs when zero absorptance is assumed for the canopy. The Duntley equations reduce to a three-parameter representation for the special case of no absorptance.

Berry, J.K. and J.A. Smith. 1977. An overview of Vegetation Canopy Modeling for Signature Correction and Analyses. 4th Annual Symp. on Machine Processing of Remotely Sensed Data. p. 194.

Summary form only given as follows: The authors discuss several applications of Canopy Modeling to the central problem of understanding and correcting signature variations. Discussion emphasizes a monte carlo model that was originally developed to investigate the bidirectional reflectance character of natural grasslands.

Boffi, V.C. and G. Spiga. 1977. Integral Theory of Radiative Heat Transfer with Anisotrophic Scattering and General Boundary Conditions. J. Math. Phys. 18(12):2448-2455.

Using the Green's function method the Boltzmann integro-differential equation is converted into a pair of integral equations. These can be formally solved by using a series expansion in legendre polynomials. Conditions for obtaining a usable solution are discussed. (13 Refs).

Buckius, R.O. and D.C. Hwang. 1978. Conservative Anisotropic Scattering in a Planar Medium with Collimated Radiation. ASME Pap. No. 78-HT-17, 8 p.

The directional hemispherical and bidirectional reflectance and transmittance are presented for a conservative anisotropic scattering medium. Collimated incident radiation and linear anisotropic scattering are considered so that the azimuthal dependence must be retained. The effects of optical thickness, anisotropic scattering, incident angle, polar angle, and aximuthal angle are presented in a closed-form approximate solution. Comparisons with exact solutions are also presented. 12 refs.

Bunnik, N.J.J. 1978. The Multispectral Reflectance of Shortwave Radiation by Agricultural Crops in Relation with their Morphological and Optical Properties. Wageningen. Mededelingen Landbouwhogeschool. Nederland 78-1. 175 p.

The objectives of the investigation and the contents of this manuscript may be summarized as follows.

1. To investigate relations between crop variables and spectral reflectance of vegetative canopies by means of an appropriate mathematical model and experimental data. Variables of uniform canopies, like total leaf area index, leaf angle distribution, optical constants of the leaves and spectral reflectance of the bounding soil have been studied in relation with geometrical variables of incoming radiation and the direction of detection of reflected radiation.
2. To determine spectral bands producing useful relations between reflectance data and canopy variables. Further, suitable combinations of reflectance data from different spectral bands have been studied which provide a simplified and better defined relationship with canopy structure, leaf colour or moisture content variations of the upper surface layer of the bounding soil. As a result of this study, a non-destructive method became available for monitoring crop growth, crop senescence, detection of changes probably related to stress or diseases and to produce data useful to crop yield estimation techniques.
3. To determine the spectral bandwidth allowed of selected wavelength bands in relation with a minimized loss of sensivity of the mensuration of spectral reflectance variations due to variations in crop structure.
4. To determine directions of incoming and reflected radiation producing a drastic simplification in the complicated relation between crop reflectance and crop variables. On account of the conditions found, monitoring of dynamic behaviour of crop properties could be carried out with increased accuracy.
5. To determine the position and a minimum number of spectral bands with a minimum loss of spectral information for between-crop type discrimination.

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Chance J.E. and E.W. LeMaster. 1977. Suits Reflectance Models for Wheat and Cotton: Theoretical and Experimental Tests. Appl. Optics 16(2): 407.

A light absorption model (LAM) for vegetative plant canopies has been derived from the Suits reflectance model. From the LAM the absorption of light in the photosynthetically active region of the spectrum (400-700 nm) has been calculated for a Penjamo wheat crop for several situations including (a) the percent absorption of the incident radiation by a canopy of LAI 3.1 having a four-layer structure, (b) the percent absorption of light by the individual layers within a four-layer canopy and by the underlying soil, (c) the percent absorption of light by each vegetative canopy layer for variable sun angle, and (d) the cumulative solar energy absorbed by the developing wheat canopy as it progresses from a single layer through its growth stages to a three-layer canopy. This calculation is also presented as a function of the leaf area index and is shown to be in agreement with experimental data reported by Kanemasu on Plainsman V wheat.

Chance J.E. and E.W. LeMaster. 1978. Plant Canopy Light Absorption Model with Application to Wheat. Appl. Optics 17(16):2629-2636.

Plant canopy reflectance models developed by Suits are tested for cotton and Penjamo winter wheat. Properties of the models are discussed, and the concept of model depth is developed. The models' predicted exchange symmetry for specular irradiance with respect to sun polar angle and observer polar angle agreed with field data for cotton and wheat. Model calculations and experimental data for wheat reflectance vs sun angle disagreed. Specular reflectance from 0.50 μm to 1.10 μm shows fair agreement between the model and wheat measurements. An Appendix includes the physical and optical parameters for wheat necessary to apply Suits' models.

Chandrasekhar, S. 1960. Radiative Transfer. New York: Dover Publication, Inc. 393 p.

Coldwell, J.E. 1974. Vegetation Canopy Reflectance. *Remote Sensing of Environment* 3:175-183.

Possible cause-effect relationships in producing vegetation canopy reflectance are discussed. Hemispherical reflectance and even bidirectional reflectance measurements are shown to be inadequate to predict or understand vegetation canopy reflectance in many situations. Among the additional important parameters necessary for prediction and understanding of vegetation canopy reflectance are leaf hemispherical transmittance, leaf area and orientation, characteristics of other components of the vegetation canopy (stalks, trunks, limbs), soil reflectance, solar zenith angle, look angle, and azimuth angle. The effects of these parameters on vegetation canopy bidirectional spectral reflectance are described.

The reflection function for an isotropically scattering medium has been expressed in terms of Chandrasekhar's X and Y functions for a finite medium and in terms of Chandrasekhar's H function for a semi-infinite medium. Expressions for the directional-hemispherical reflectance, hemispherical-directional reflectance and hemispherical reflectance have been presented in terms of the X, Y, and H functions and their moments. Also, asymptotic expressions have been presented.

Crosbie, A.L. 1973. Reflection Function for an Isotropically Scattering Finite Medium. *AIAA J.* 11(10):1448-1450.

The reflection function for an isotropically scattering medium has been expressed in terms of Chandrasekhar's X and Y functions for a finite medium and in terms of Chandrasekhar's H function for a semi-infinite medium. Expressions for the directional-hemispherical reflectance, hemispherical-directional reflectance and hemispherical reflectance have been presented in terms of the X, Y, and H functions and their moments. Also, asymptotic expressions have been presented.

Duntley, S.Q. 1942. The Optical Properties of Diffusing Materials. *Journal of the Optical Society of America* 32(2):61-70.

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Duntley, S.Q. 1969. Directional Reflectance of Atmospheric Paths of Sight. Report No. 69-11; USGRDR No. AD-688 265. La Jolla, Calif.

The Contrast reducing properties of any path of sight inclined downward through the atmosphere can be specified by a single dimensionless number analogous to a reflectance and called the directional reflectance of the path of sight by ratio of the directional path reflectance to the inherent directional reflectance of the background. Previously published optical atmospheric data derived from in-flight measurements have been used to produce tables of R. For two clear-weather conditions. A simple nomograph and numerical examples are included.

Egan, W. G., J. Grusauskas, and H. B. Hallock. 1968. OPTICAL DEPOLARIZATION PROPERTIES OF SURFACES ILLUMINATED BY COHERENT LIGHT. Reprinted from Applied Optics, Vol. 7, page 1529, August 1968.

An experimental investigation of the depolarization characteristics of complex surfaces illuminated by 6328-A laser radiation was made on a large scale polarimeter. Measurements were made on specimens such as basalt, limonite, volcanic ash, wet and dry sand, gravel, silt, and foliage in various states of freshness. (For powders and aggregates, depolarization appears more pronounced as the size of the individual particles decreases, and as the roughness and porosity of the surface features increases, whereas depolarization appears less pronounced as water is adsorbed or absorbed.) The depolarization signature of foliage served to characterize a particular species, and dryness of the specimens tended to increase the depolarization. As a practical outcome, it appears that additional surface characterization or signature can be obtained through measurement of depolarization characteristics.

Fowler, W. B., E.I. Reed, and J.E. Blamont. 1971. Bidirectional Reflectance of the Moonlit Earth. Appl. Opt. 10(12): 2657-2660.

From OGO-4 Airglow Photometer data and computed lunar spectral irradiances at the subsatellite point. The highest radiance over clouds and lowest radiance over open ocean are examined near 3914A, 5577 A, 5893 A, 6225 A, and 6300 A in terms of bidirectional reflectance. The results are compared to and are consistent with mathematical models of the atmosphere developed by Plass and Kattawar 7a. And with daytime measurements from OGO-3 by Neel, Griffin, and Millard.

Fraser, R.S. and W.H. Walker. 1968. Effect of Specular Reflection at the Ground on Light Scattered from a Rayleigh Atmosphere. J. Opt. Soc. Am. 58(5):636-644.

The method of Chandrasekhar is used to compute the parameters that characterize the scattered light leaving the top of a Rayleigh atmosphere. The atmosphere of this model lies above a smooth water surface, which reflects light according to Fresnel's law. The combined atmosphere and water is called the Fresnel model. The results for the Fresnel model are compared with corresponding results for a second model, which is called the Lambert model, since its ground reflects light according to Lambert's law. The reflectance at the ground is less than 0.1, if either the solar zenith angle $\theta_0 < 65°$ or the total optical thickness $\tau_1 > 0.6$. The relative difference between the outward fluxes from the tops of the atmospheres of the two models is less than 0.07 if $\theta_0 < 84°$. The difference between the radiances of the nadirs at the tops of the two models is less than 0.1 if $\tau_1 > 0.5$, but the difference becomes large at small τ_1. The maximum degree of polarization and the neutral-point positions at the top of the atmosphere of the Fresnel model are quite different from those of the Lambert model, when the total optical thickness is less than 0.5. The neutral points for the Fresnel model appear outside of the vertical plane through the sun for restricted ranges of both the total normal optical thickness and the solar zenith angle.

Goudriaan, J. 1977. Crop Micrometeorology: A Simulation Study. Wageningen, the Netherlands: Centre for Agricultural Publishing and Documentation. 249 p.

Hering, R.G. and T.F. Smith. 1970. Surface Roughness Effects on Radiant Energy Interchange. ASME Pap. 70-HT/SpT-2. 9 p.

Radiant interchange between opaque interacting surfaces is formulated for unequal temperature adjoint plates with a one-dimensional surface roughness profile. Rough surface bidirectional reflectance and directional emittance depend on material emittance, roughness element slope, and roughness element specularity. Absorption factor results show a strong dependence on surface roughness and indicate that roughness effects are more important in the evaluation of radiant interchange than radiant heat loss. Absorption factor values differing by a factor of two to four are commonly observed for identical emittance materials as a result of roughness. 12

Horn, B.K.P. Understanding Image Intensity. Artif. Intell. 8 (April 1977), 201-231.

Traditionally, image intensities have been processed to segment on image into regions or to find olge-fragements. Image insensities carry a great deal more information about three-dimensional shape, however. To exploit this information, it is necessary to understand how images are formed and what determines the observed intensity in the image. The gradient space, p ularized by Huffman and Mackworth in a slight different context, is a helpful too in the development of new methods.

Idso, S.B. and C.T. deWit. 1970. Light Relations in Plant Canopies. Appl. Optics 9(1):177-184.

A theory of light relations in plant canopies is presented which has potential applications in remote sensing and photosynthetic modeling of plant canopies. Predictions of the model are compared with filed measurement of light reflection and transmission in a corn crop. Both reflection at the top if the canopy and transmission at the bottom are predicted within 1 percent of the measured values. Profiles connecting these upper and lower limits are equally well approximated. Varitions in the predictions with altitude angle of the sun are confirmed by the observation of several investigators.

Ishimaru, A. 1977. Theory and Application of Wave Propagation and Scattering in Random Media. Proc. of the IEEE 65(7):1030-1061.

Abstract -- This paper presents a review of basic theories and recent advances in the studies of wave propagation and scattering in random media. Examples of the random media include the atmosphere, the ocean, and biological media whose characteristics are randomly varying in time and space. The study of electromagnetic, optical, and acoustic waves in such media has become increasingly important in recent years primarily in the areas of communication, detection, and remote sensing. Topics covered in this paper are divided into "waves in randomly distributed scatters," "waves in random continua," and "remote-sensing of random media." Transport theory with various approximate solutions and multiple scattering theories are discussed and their relationship are clarified. Included in the analyses are propagation characteristics of intensities, wave fluctuations, pulse propagation and scattering, coherence bandwidth, and coherence time of communication channels through random media. Remote-sensing techniques include recent advances in the use of inversion to deal with ill-posed problems.

Kimes, D.S., J.A. Smith and K.J. Ranson. 1979. Terrain Feature Canopy Modeling. Final Report. U.S. Army Research Office, Grant Number DAAG 29-78-G-0045. 111 p.

A thermal canopy signature model (TCSM) was developed to approximate the thermal behavior of a vegetation canopy by a mathematical abstraction of three horizontal layers of vegetation. Canopy geometry within each layer is quantitatively described by the foliage and branch orientation distributions. 20. Canopy geometry, solar irradiance, air temperature, horizontal wind velocity, relative humidity, and ground temperature are used to calculate the energy budgets of average leaves within each layer. The resulting system of conservation equations is solved for the average layer temperature. This information, together with the angular distributions of radiating elements, is then used to calculate the thermal exitance as a function of view angle above the canopy. Optical diffraction techniques were developed and employed to measure canopy geometry. Solar radiation absorption with the vegetation terrain elements is calculated using a modification of a Monte Carlo model (SRVC) developed for the reflective energy regime.

The models were applied to a lodgepole pine (Pinus contorta) canopy and the results for a diurnal cycle are validated with radiometric measurements. Simulated versus measured radiometric average temperatures of Layer 2 correspon approximately within two degrees centigrade. Simulated results suggest that canopy geometry can significantly influence the effective radiant temperature recorded by a sensor above the canopy as a function of view angle.

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Kriebel, K.T., H. Quenzel and W. Scholze. 1976. On the Determination of the Atmospheric Air Light as a Normally Underestimated Perturbation Signal. Atmospheric Environment 10:645-653.

Abstract -- A simple method to compute the air light, based on single scattering only, is compared with an exact iterative method including multiple scattering and is found to give reasonable values of the air light expressed as a percentage of the reflected radiance. Besides some general dependencies of the air light for four different geometrical situations the air light is shown as a percentage of the total radiation received by snesor at arbitrary heights as a function of the atmospheric turbidity.

Leader, J.D. 1971. Bidirectional Scattering of Electromagnetic Waves from Rough Surfaces. J. Appl. Phys. 22(12):4808.

A general bidirectional expression is derived from the Station-Chu-Silver integral for the scattering of electromagnetic waves from rough surfaces. This expression is then exapanded in a power series of surface slope terms for the special case of scattering in the plane of incidence. The results of this expansion are then compared with other models and closed-form solutions are obtained for comparison with experiment.

Malila, W.A. R.C. Cicone, and J.M. Gleason. 1976. Wheat Signature Modeling and Analysis for Improved Training Statistics: Supplement. Simulated LANDSAT Wheat Radiances and Radiance Components. Final Report, ERIM 109600-66-F_s. Environmental Research Institute of Michigan, the University of Michigan, Ann Arbor, Michigan. 187 p.

This supplement presents in detail a series of simulated scanner system data values generated in support of LACIE (Large Area Crop Inventory Experiment) research and development efforts. Synthetic inband (Landsat) wheat radiances and radiance components were computed and are presented for various wheat canopy and atmospheric conditions and scanner view geometries. Values include:

(1) inband (Landsat) bidirectional reflectances for seven stages of wheat crop growth,

(2) inband (Landsat) atmospheric features, and

(3) inband (Landsat) radiances corresponding to the various combinations of wheat canopy and atmospheric conditions.

Analyses of these data values are presented in the main report.

Maxwell, J.R. and S.F. Weiner. 1974. Polarized Emittance. Volume 1: Polarized Bidirectional Reflectance with Lambertian or Non-Lambertian Diffuse Components. Final Report. ERIM-192500-1-T(1), Contract DAAD05-72-C-0246. Ann Arbor, Mich.

Abstract: Volume I of this report provides the Ballistic Research Laboratories with a discussion of the algorithms upon which the bidirectional reflectance model is based, in particular the non-Lambertian volume model which was constructed under this contract. The report provides a validation of the model with respect to the materials supplied by BRL. It includes a listing of appropriate model parameters with a description of how to use the model, and a listing of the computer program with its subroutines. The model makes it possible to calculate bidirectional reflectance data from a very small amount of measured data. Accuracy demonstrated indicates that the model is very effective, although improvement can still be obtained at large receiver zenith angles. (Author)

Maxwell, J.R. and S. Weiner. 1974. Polarized Radiance. Volume III: Wavelength Dependence of Polarized Bidirectional Reflectional Reflectance. Final Report. ERIM-19500-1-T(3), Contract DAAD05-72-C-0246. Ann Arbor, Mich.

Abstract: Volume III of this report provides the Ballistic Research Laboratories with a method for extracting information from a limited set of directional and bidirectional reflectance measurements so as to provide a wavelength-corrected input to the volume component of the bidirectional reflectance model described in Volume I. It is shown that the surface component of the bidirectional reflectance has little wavelength dependence for the materials studies from 0.63 micrometers, and 3.39 micrometers and 10.6 micrometers under this contract are included and are used for the model validation which is also described. (Author).

Norman, J.M., S.G. Perry, A.B. Fraser and W. Mach. 1979. Remote Sensing of Canopy Structure. Fourteenth Conf. on Agriculture & Forest Meteorology and Fourth Conf. on Biometeorology 184-185.

Oliver, R.E. and J.A. Smith. 1973. Vegetation Canopy Reflectance Models. Final Report, Contract No. DA-ARO-D-31-124-71-G165. 91 p.

Stochastic and deterministic approaches to simulating the spectroreflectance of shortgrass prairie vegetation have been investigated. The stochastic approach utilizes randomly selected variates for incoming light flux, plant geometry, and intrinsic optical properties whereas the deterministic model is patterned after the familiar Kubelka-Munk theory for diffuse reflectance.

The stochastic model was deemed more desirable because of its flexibility and inherent capability of providing the multivariate covariances. This model determines the apparent directional reflectance which is dependent upon both sun and view angles as well as canopy geometric and optical properties and soil background. The model results are compared with field and laboratory measurements of Blue grama (Bouteloua gracilis) and successfully predicts the non-Lambertian character of the canopy.

The site of the field measurements was the Pawnee National Grasslands, the intensive study site of the International Biological Program. Direct solar and diffuse sky irradiance and the optical properties of Blue grama were measured in the 0.4 micrometer to 1.05 micrometers region of the spectrum using a field adapted EG&G spectroradiometer with a computer based digital acquisition system. Canopy geometry was measured with a laboratory photographic technique with subsequent digitization of the profile images.

Oliver, R.E. and J.A. Smith. 1974. A Stochastic Canopy Model of Diurnal Reflectance. Final Report. U.S. Army Research Office Durham. DAHC04 74 G0001. 82 p.

The spectral signature of most vegetation varies with both direction of view and time of day. This variation is spectrally dependent and is due primarily to differences in canopy geometry. As a means of investigating the interaction of shortwave radiation with vegetation a stochastic canopy model was developed. The model utilizes random variables based on measured distributions for incoming radiation flux, intrinsic optical properties, and canopy geometry. Two methods were used for determining canopy geometry. The first method is to orthogonally project and photograph individual plants and to directly measure the leaf angles from the photographs. The second method is a rapid *in situ* technique involving the solution of a Fredholm integral equation based on data from ground level photography. A portable battery powered spectrometer system was constructed for the measurement of vegetation apparent directional reflectance. This instrument provides data for model validation and horizontal surface irradiance measures required as model input. A direct application of the model is to simulate statistical spectral signatures for use with remote sensing pattern recognition algorithms. A qualitative study was made to investigate the effects of changing canopy directional reflectance on feature selection. The results show that different combinations of wavelength channels are appropriate for various sensor look angles, that target signatures have greater statistical separation for some scan angles than others, and that these effects are time varying.

Preisendorfer, R. W. 1965. Radiative Transfer on Discrete Spaces. Pergamon Press. 462 p.

Reichman, J. 1973. Determination of Absorption and Scattering Coefficients for Nonhomogeneous Media. I. Theory. Appl. Opt. 12(8):1311-1315.

Equations are derived to determine the diffuse reflectance and transmittance of inhomogeneous materials. The equations are valid for collimated incident radiation for any angle of incidence. The effects of Boundary reflectance and anisoptrophic scattering are included. The equations are derived from the equation of radiative transport, Using the Schuster-Schwartzchile approximation. They are sufficiently simple to be used for spectroscopic determination of the absorption and scattering coefficients. Numeral comparison with more exact solutions of the equation of radiative transfer show very good agreement for all cases except for reflectance in the highly anisotrophic case, where agreement is only fair . (11 refs)

Ross, J. 1976. Radiative Transfer in Plant Communities. In: Vegetation and the Atmosphere. Vol. I. Principles. (Ed: J.L. Monteith), Academic Press, London. pp. 13-55.

Smith, J.A. and R.E. Oliver. 1972. Plant Canopy Models for Simulating Composite Scene Spectroadiance in the 0.4 to 1.05 Micrometer Region. Eight Symposium on Remote Sensing of the Environment, University of Michigan, Ann Arbor, 2:1333-1353.

A Monte Carlo Model has been developed for simulating the interaction of direct and diffuse shortwave radiation with the canopy of shortgrass prairie vegetation (*Bouteloua gracilis*). The model treats the canopy as consisting of layered statistical ensembles of foliage elements against a soil background. The model allows for multicomponent mixtures possessing different spectral and foliar display characteristics. Light flux, whose variables include wavelength and diffuse and direct components, is traced through nonuniform layers using stochastic canopy structure and interaction probabilities that vary with illumination angle, foliage angle distribution, and leaf-area index. Initially, a Lambertian spatial response of the reflecting/transmitting elements has been assumed.

A two-layer canopy containing only one constituent and a soil background is simulated. Geometric characteristics of the foliage, optical properties of the leaves and soil, and spectroradiance determinations were obtained by the authors during the 1972 summer field season. The model correctly accounted for the apparent directional reflectance of the canopy as seen by a vertical view sensor for all wavelengths between 0.4 and 1.05 micrometers except at the chlorophyll absorption region between 0.65 and 0.70 micrometers. The single constituent model was not able to account for the apparent directional reflectance for the canopy for a sensor inclined at 40 degrees from the zenith. It is hypothesized that the model would need to be run with a second constituent, also present in the canopy, to account for this disagreement.

The non-Lambertian character of the apparent directional reflectance of the canopy is demonstrated and an increased spectral return for the sensor view angle containing the solar disk are predicted. A comparison of the two-parameter Kubelka-Munk Model with measured field data is also given.

Smith, T.F. and R.G. Hering. 1972. Bidirectional Reflectance of a Randomly Rough Surface. Prog. Astronaut. Aeronaut., Fundam. of Spacecr. Therm. Des. 29:69-85.

A bidirectional reflectance model is developed for a one-dimensionally rough surface consisting of V-shaped roughness elements with randomly distributed slopes. Multiple reflections within and shadowing by adjacent roughness elements are accounted for in the model. A distribution function in terms of rms slope is utilized to specify the probability that a macroscopic surface reflects specularly, and energy experiencing multiple reflections is unimportant. Multiple reflections become increasingly significant for larger rms slopes. This importance, however, diminishes as the direction of incident energy approaches grazing incidence. The model exhibits characteristics similar to those observed in recent bidirectional reflectance data. 11 refs.

Smith, T.F. and R.G. Hering. 1973. Comparison of the Beckman Model with Bidirectional Reflectance Measurements. ASME paper no. 73-HT-11. 13 p.

Comparisons revealed that monochromatic specular and bidirectional reflectance measurements are not adequately described by corresponding results evaluated from the model using mechanically acquired surface roughness parameters rms height and rms slope. Significant improvement between measurements and predictions of the model is observed when optically acquired surface roughness parameters are used. Specular reflectance measurements for normal to intermediate polar angles of incidence are adequately represented by the model provided values of optical roughness multiplied by cosine of polar angle of incidence are less than 27 times average optical rms slope. Optical roughness is the ratio of optical rms height to wavelength of incident energy. Bidirectional reflectance measurements are adequately predicted by the model when values of optical roughness and optical rms slope are less than 0. 05 and 0. 02, respectively.

G.H. Suits (1972a), The Calculation of the Directional Reflectance of a Vegative Canopy. Remote Sensing Environ. 2, 117-125.

Gwynn H. Suits (1972b), The cause of Azimuthal Variations in Directional Reflectance of Vegetative Canopies. Remote Sensing Environ. 22, 175-182.

The variation of the directional reflectance of a vegetative canopy with azimuthal view angle becomes prominent when the canopy is illuminated by the sun at large angles from zenith. An extension of a previous directional reflectance model of vegetative canopies is presented to quantify this effect. The results indicate that the cause of the azimuthal variation can be traced to solar flux illumination of the vertically oriented canopy components and that the extreme variations of reflectance with aximuth of view are moderated by the azimuthally isotrophic sources of flux from skylight and canopy.

Suits, G.H. and G. Safir. 1972. Prediction of Directional Reflectance of a Corn Field Under Stress. Fourth Ann. Earth Resources Program Review, V. 2, 11 p.

The remote sensing of sympto,s of pathological conditions in vegetative canopies such as Southern Corn Leaf Blight depends upon a consistent relationship between the pathological systoms and the remotely sensed effects. The use of training sets show only that in particular cases, and at a particular time, a certain pathological condition occurs concurrently with some remotely sensed effect. There may be no necessary connection between them. The use of a mathematical model to predict the remotely sensed effect from the fundamental biological causes allows one to establish the expected consistency between the conditions and the sensed effects as well as to provide insight leading to the "best remote sensing techniques to use for a particular application.

A new method of calculating the directional reflectance of a vegetative canopy (1) has been used to calculate the directional spectral reflectance of a corn canopy under stress. The comparison of predicted reflectance with field measurements indicate that the model is sufficiently accurate when applied to corn fields to warrant the use of the model for application to other conditions. The prediction of the expected reflectance differences between a healthy and a bilighted one-month old corn field illustrates the application to other conditions.

Suits, G.H., and Safir, G.R. (1972). Verification of a Reflectance Model for mature Corn with Applications to Corn Blight Detection, Remote Sens. Environ. 2, 183.

A new model for calculating the directional spectral reflectance of vegetative canopies was verified for the case of mature corn by field reflectance measurements on two different mature corn fields at each of two viewing angles and over the visible and near infrared spectral bands. The application of the model to hypothetical conditions indicates that moderately severe Southern Corn Leaf Blight should be marginally detectable by aerial photography under certain special circumstances and that for more severe blight, the blight condition should be distinguishable from moisture stress. The application of the model to hypothetical fields of young corn indicates that the blight condition should be easily detected under a wide range of circumstances.

Suits, G.H., R.K. Vincent, H.M. Horwitz, and J.D. Erickson. 1973. Optical Modeling of Agricultural Fields and Rough-textured Rock and Mineral Surfaces. Informal Technical Report, ERIM 31650-78-T Environmental Research Institute of Michigan, The University of Michigan. 37 p.

To improve the ability to utilize laboratory spectra for predicting or interpreting airborne scanner data, a search was made for two theoretical models, one to calculate the reflectance of plant canopies and the other to assess the effect of textural variations on the spectral emittance or reflectance of natural rock surfaces. Several models were reviewed, from which it was possible to select the types of models best suited for these applications. The selected plant canopy model, an extension of the Allen-Gayle-Richardson model, can be used to predict the bidirectional reflectance of a field crop from known laboratory spectra of crop components and approximate plant geometry (planting density and average horizontal and vertical component cross-sections). It is applicable even to vegetative targets composed of multiple canopy layers. Bidirectional reflectances of two corn fields calculated from the canopy model were found to agree with laboratory data within an extremum error of 15% in $\frac{\Delta\rho}{\rho}$. The selected geological model which is to be developed later will permit calculation of spectral emittance spectra for different textured rock surfaces, even though the rock may contain randomly oriented birefringent crystals and may consist of several different minerals. The resulting emittance spectra for various particle diameters will be used to predict the effect of textu al variations on an infrared ratio method used previo to image large compositional variations in silicate rocks with airborne or space-borne multispectral scanner data. An adequate atmospheric radiative transfer model exists to calculate the atmospheric effects between such targets and remote spectral sensors.

Verhoef, W. and N.J.J. Bunnik. 1975. A Model Study on the Relationships Between Crop Characteristics and Canopy Spectral Reflectance. NIWARS, Delft, publ. No. 33.

Verhoef, W. and N.J.J. Bunnik. 1976. The Spectral Directional Reflectance of Row Crops. Part 1: Consequences of Non-Lambertian Behaviour for Automatic Classification. Part 2: Measurements on Wheat and Simulations by Means of a Reflectance Model for Row Crops. Report No. NIWARS-PUBL-35. Netherlands Interdepartmental Working Group on the Application of Remote Sensing, Delft. 144 p.

Abstract: The one-layer Suits model for canopy reflectance was applied to simulate a multispectral scanning flight over an agricultural area. Non-Lambertian behavior and misclassification were studied on the basis of unprocessed and preprocessed data from the reflectance simulations. A new experimental model for the calculation of the directional reflectance of row crops, based on the one-layer Suits model, is presented. This model was applied to simulate measurements of the spectral directional reflectance on mechanically sowed wheat at several growth stages in the summer of 1974. In general, input and output data of both model and field data agree well. Specular reflection at leaves, not incorporated in the present model, appears to be a significant factor for crop reflectance.

Weinman, J.A. and P.J. Guetter. 1972. Penetration of Solar Irradiances Through the Atmosphere and Plant Canopies. J. Appl. Meteorology 11:136-140.

The equation of radiative transfer is applied to the analysis of solar irradiances penetrating into a plant canopy covered by a turbid atmosphere. The method of discrete coordinates is applied to vertically inhomogeneous atmospheres and plant canopies. It is shown that four-point quadrature yields results with an accuracy which is consistent with irradiance measurements.

Welles, J. M. and J. M. Norman. 1979. General Radiative Transfer Model for Random and Non-random Canopies. Fourteenth Conf. on Agriculture & Forest Meteorology and Fourth Conf. on Biometerorology. 205-206.

The most sophisticated radiative transfer models apply to canopies of a large horizontal extent and are thus more or less one dimensional. Some efforts have considered the non-random distribution of foliage over the vertical and horizontal with formulations that remain fundamentally one dimensional. For dense canopies of leaves of nonoverlapping crowns, it has been customary to use projections of various opaque shapes such as cones, trapezoids, cylinders, rectangles, etc.
The model used here is very general including multiple scattering for near-infrared and solar wavelengths and emission for thermal wavelengths. It is applied to an array of individual canopies which may or may not be overlapping.

II. MEASUREMENTS

A. LABORATORY

B. FIELD

C. PLATFORM (AIRCRAFT AND SATELLITE)

II. MEASUREMENTS

A. LABORATORY

17 references

Blanchard, M. B., R. Greeley, and R. Goettelman. 1974. Use of Visible, Near-infrared, and Thermal Infrared Remote Sensing to Study Soil Moisture. <u>Proc. of the 9th Int. Symp. on Remote Sensing of Environ.</u> v. 1:693-700.

Two methods are used to estimate soil moisture remotely using the 0.4- to 14.0-micron wavelength region: measurement of spectral reflectance, and measurement of soil temperature. The reflectance method is based on observations which show that directional reflectance decreases as soil moisture increases for a given material. the soil temperature method is based on observations which show that differences between daytime and nighttime soil temperatures decrease as moisture content increases for a given material. In some circumstances, separate reflectance or temperature measurements yield ambiguous data, in which case these two methods may be combined to obtain a valid soil moisture determination. Refs.

Breece, H. T. (III) and R. A. Holmes. 1971. Bidirectional Scattering Characteristics of Healthy Green Soybean and Corn Leaves in Vivo. Appl. Opt. 10 (1): 119-127.

Bidirectional reflection and transmission distribution functions are measured for healthy green soybean and corn leaves *in vivo*, for nineteen narrow wavelength bands from 375 nm to 1000 nm. Off-normal incidence reflection distribution functions show considerable specular contributions at wavelengths of strong absorption, while transmission distribution functions show a near-lambertian shape for all wavelengths employed. An empirical *m*-layer leaf model affords a reasonable qualitative understanding of these scattering distributions.

Christie, F.A. and A. B. DeVriendt, 1972. Bidirectional Reflectance from Surfaces Formed by the Ruling of Orthogonal Parallel V-Grooves. Report on Thermal Control and Radiation. Presented at the ALAA Aerospace Sciences Meeting (10th). Paper No. 72-55.

Abstract: Experimentally and photographically determined bidirectional reflectance data are presented for a set of sixteen regularly rough surfaces composed of square pyramids, which were illuminated by a He-Ne laser beam (0.6328 micrometer). The included angles of the ruled V-grooves were 60, 90, 120 and 150 degrees while the peak-to-valley depths were 2.5, 5, 10, and 20 micrometers. Agreement between the theoretical and experimental data was satisfactory and improved as the included angle increased. For most angles of incidence, three-dimensional theory was required to predict the bidirectional reflectance because of the effects of shadowing, masking, and interreflection. (Author)

Christie, F.A. and A.B. DeVriendt. 1973. Diffraction Effects Encountered in the Measurement of Bidirectional Reflectance from Square Pyramid. Proc. of the ALAA Aerospace Sciences Meeting (11th). Paper No. 73-150

Abstract: Theoretically and photographically determined bidirectional reflectance data are presented for a set of sixteen regularly rough surfaces composed of square pyramids which were illuminated by a He-Ne laser beam. The included angles of the ruled V-grooves were 60, 90, 120 and 150 degrees, while the peak-to-valley depths were 2.5, 5, 10 and 20 microns. The photographs graphically illustrate a smooth transition from reflectance patterns predicted by diffraction theory to others described by conventional bidirectional reflectance theory. Although precise measurement is difficult in some diffuse patterns, agreement between the theoretical and photographic data was generally one degree or less.

Coulson, K. L. 1966. Effects of Reflection Properties of Natural Surfaces In Aerial Reconnaissance. Appl. Opt. 5(6):905-917.

Measurements of the reflecting and polarizing properties of various soils, sands, and vegetation in the visible- and near-ir spectral regions show that dark surfaces polarize the reflected radiation strongly while highly reflecting surfaces have relatively weak polarizing properties. In general, the reflectance of mineral surfaces increases, and the degree of polarization of the reflected radiation decreases, with increasing wavelength and increasing angle of incidence. There is little or no indication of specular reflection from the surfaces for which measurements were made. Introduction of the reflection data into the equation of radiative transfer for clear and slightly turbid models of the earth's atmosphere shows that the upward radiation that would be incident on a high-altitude aircraft or satellite would be dominated by surface-reflected radiation for the red and near-ir regions over highly reflecting surfaces such as deserts, whereas atmospheric scattering is most important for short wavelengths and dark surfaces. Because of polarization effects, atmospheric transmission of optical contrasts is better in one orthogonal intensity component than the other, the difference being sufficient to merit polarizing optics in reconnaissance instrumentation under certain conditions.

Coulson, K. L., G. M. Bocuricius, and E. L. Gray. 1965. Optical Reflection Properties of Natural Surfaces. J. Geophysical Res. 70(18):4601-4611.

Measurements of the optical reflection characteristics of various natural sands and soils at wavelengths of 4920 A, 6430 A, and 7960 A are presented. It is shown that there is a strong dependence of the intensity and degree of polarization of the reflected radiation on angle of incidence of the radiation azimuth and elevation angles at which the surface is viewed, wavelength of the radiation and physical state of the surface itself. A comparison of these measurements with those of other authors shows that the reflectance values obtained here are generally similar to those obtained by Krinov under similar conditions, but the degree of polarization of radiation reflected from the various sands is considerably less than the polarization values observed by Dollfus for sand.

Egan, W.G. 1970. Optical Strokes Parameters for Farm Crop Identification. Remote Sensing of Environ. 1:165-180.

The use of bidirectional polarization and photometry implies the efficient use of all the optical information available in the scattered radiation. This information is represented as Stokes parameters,' which include wavelength, geometry, and bidirectional photometric and polarization factors. The Stokes parameters were determined in the laboratory on field crop samples of fully developed alfalfa, Long Island potatoes, sweet corn, rye, and wheat, at wavelengths of 0.350, 0.433, 0.533, 0.566, 0.633, 0.8, and 1.0 μ. The results indicate that the information available from the Stokes parameters aids in the characterization of agricultural crops.

Egan, W.G., J. Grusauskas, and H. B. Hallock. 1968. Optical Depolarization Properties of Surfaces Illuminated by Coherent Light. Appl. Optics 7(8): 1529-1534.

An experimental investigation of the depolarization characteristics of complex surfaces illuminated by 6328-Å laser radiation was made on a large scale polarimeter. Measurements were made on specimens such as basalt, limonite, volcanic ash, wet and dry sand, gravel, silt, and foliage in various states of freshness. (For powders and aggregates, depolarization appears more pronounced as the size of the individual particles decreases, and as the roughness and porosity of the surface features increases, whereas depolarization appears less pronounced as water is adsorbed or absorbed.) The depolarization signature of foliage served to characterize a particular species, and dryness of the specimens tended to increase the depolarization. As a practical outcome, it appears that additional surface characterization or signature can be obtained through measurement of depolarization characteristics.

Gates, David M., Harry J. Keegan, John C. Schleter, and Victor R. Weidner. "Spectral Properties of Plants." (Applied Optics, January, 1965, Vol. 4, No. 1.)

ABSTRACT:

The spectral properties of plant leaves and stems have been obtained for ultraviolet, visible, and infrared frequencies. The spectral reflectance, transmittance, and absorptance for certain plants is given. The mechanism by which radiant energy interacts with a leaf is discussed, including the presence of plant pigments. Examples are given concerning the amount of absorbed solar radiation for clear sky and overcast conditions. The spectral properties of desert plants are compared with those of more mesic plants. The evolution of the spectral properties of plant leaves during the early growing season is given as well as the colorimetric behavior during the autumn.

Hapke, B. and H. Van Horn, 1963. Photometric Studies of Complex Surfaces, with Applications to the Moon. J. Geophys. Res. 68(15):4545-4570.

Abstract The reflection laws of a wide variety of surfaces have been measured. The factors that govern the optical scattering characteristics of complex surfaces are discussed, and the properties of surfaces that scatter light like the moon are specified. Surfaces of solid rocks, volcanic slags, or coarsely ground rock powders do not have the intricate structure necessary for backscattering light strongly, but finely pulverized dielectric particles can build extremely complex surfaces that can reproduce the lunar scattering law. It is concluded that the surface of the moon is covered with a layer of fine rock dust composed of particles of the order of 10-micron average diameter and that 90 per cent of the volume of the surface layer is voids.

Hunt, G. R. and J. W. Salisbury. 1976. Visible and Near Infrared Spectra of Minerals and Rocks. XI. Sedimentary Rocks. Mod. Geol. 5(4):211-217.

FOR PT.X SEE IBID.. VOL.5, NO.2, P.115 (1975). BIDIRECTIONAL REFLECTANCE SPECTRA OF 24 SEDIMENTARY ROCKS (SHALES, SANDSTONES AND LIMESTONES) ARE PRESENTED FROM 0.325 TO 2.5 MUM. THE SPECTRA OF PARTICULATE SAMPLES ARE DISCUSSED, AND IT IS FOUND THAT THE MAJORITY OF FEATURES ARE CAUSED BY HYDROXYL, WATER OR CARBONATE OVERTONE AND COMBINATION TONES, OR BY ELECTRONIC TRANSITIONS IN IRON. IN MANY CASES THESE FEATURES ARE ASSOCIATED WITH CONSTITUENTS THAT OCCUR AS CEMENTS OR IMPURITIES, AND IN MOST CASES THE SPECTRAL FEATURES ARE ONLY AN INDIRECT INDICATION OF ROCK COMPOSITION (12 Refs)

Hunt, G. R. and J. W. Salisburgy. 1976. Visible and Near Infrared Spectra of Minerals and Rocks. XII. Metamorphic Rocks. Mod. Geol. 5(4):319-228.

For PT.XI See IBID. Vol. 5, No. 4, p. 211 (1976). Bidirectional reflectance spectra of 35 metamorphic rocks (marbles, quartzites, gneisses, slates and schists) are presented from 0.325 to 2.5 mm. It is found that spectral features are caused by carbonate, hydroxyl, water and borate vibrational overtone and combination tones, or by electronic transitions in iron, manganese, or chromium. In most cases these spectral features are only an indirect indication of rock composition (16 Refs.)

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King, L. E. 1976. Measurement of Directional Reflectance of Pavement Surfaces and Development of Computer Techniques for Calculating Luminance. J. Illum. Eng. Soc. 5(2):118-126.

This investigation developed and used a directional reflectance guniometer to measure the directional reflectances of eleven nine-inch pavement core samples. Five asphalt and six concrete. An electronic data processing program for calculating roadway luminance based on the reflectance data obtained from the samples, was developed and reported (14 Refs).

Loehrlein, J. E., E. R. F. Winter, and R. Viskanta. 1971. Measurement of Bidirectional Reflectance Using a Photographic Technique. IN: American Inst. Aeronautics and Astronautics. J.W. Lucas (Ed). M.I.T. Publ., Cambridge, Mass. 231-48pp.

A PHOTOGRAPHIC TECHNIQUE FOR MEASURING THE ANGULAR DISTRIBUTION OF MONOCHROMATIC RADIATION REFLECTED FROM SURFACES IS DESCRIBED. RELATIVE MEASUREMENTS ARE REPORTED ON BOTH A QUALITATIVE AND QUANTITATIVE BASIS FOR TWO SPECIMENS OF WELL-CHARACTERIZED V-GROOVE, VERY SMOOTH ALUMINUM, POLYCRYSTALINE MAGNESIUM OXIDE AND PROJECTION SCREEN SURFACES IN THE VISIBLE PART OF THE SPECTRUM FOR A RANGE OF POLAR ANGLES OF INCIDENCE (21 Refs)

Loveridge, R. C. and S.R. Scheele. 1973. UGT Post Test Light Scattering Measurements. Final Report, Contract F04701-72-C-0299. 66 p.

Abstract: The purpose of this program was to measure large angle radiation scattering from materials. Transmitting elements, baffles, and mirrors were used. The measurements were made at 0.6238, 1.15, 3.38, and 10.6 microns and at angles of from 1 to 45 degrees. (Author).

Smith, T.F. and R. G. Hering. 1972. Surface Roughness Effects on Bidirectional Reflectance. Rept. No. UILU-ENG-72-4001; ME-TR-661-2. Contract NAS7-100, JPL-951661. 126 p.

Abstract: An experimental study of surface roughness effects on bidirectional reflectance of metallic surfaces is presented. A facility capable of irradiating a sample from normal to grazing incidence and recording plane of incidence bidirectional reflectance measurements was developed. Samples consisting of glass, aluminum alloy, and stainless steel materials were selected for examination. Samples were roughened using standard grinding techniques and coated with a radiatively opaque layer of pure aluminum. Mechanical surface roughness parameters, rms heights and rms slopes, evaluated from digitized surface profile measurements are less than 1.0 micrometers and 0.28, respectively. Rough surface specular, bidirectional, and directional reflectance measurements for selected values of polar angle of incidence and wavelength of incident energy within the spectral range of 1 to 14 micrometers are reported. The Beckmann bidirectional reflectance model is compared with reflectance measurements to establish its usefulness in describing the magnitude and spatial distribution of energy reflected from rough surfaces.

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Watson, R.D. 1972. Spectral Reflectance and Photometric Properties of Selected Rocks. Rem. Sens. Environ. 2:95-100.

Studies of the spectral reflectance and photometric properties of selected rocks at the USGS Mill Creek, Oklahoma, remote sensing test site demonstrate that discrimination of rock types is possible through reflection measurements, but that the discrimination is complicated by surface conditions, such as weathering and lichen growth. Comparisons between fresh-broken, weathered, and lichen-covered granite show that whereas both degree of weathering and amount of lichen cover change the reflectance quality of the granite, lichen cover also considerably changes the photometric properties of the granite. Measurements of the spectral reflectance normal to the surface of both limestone and dolomite show limestone to be more reflective than dolomite in the wavelength range from 380 to 1550 nanometers. The reflectance difference decreases at view angles greater than 40° owing to the difference in the photometric properties of dolomite and limestone.

II. MEASUREMENTS

B. FIELD

25 references

Bauer, M.E., M.M. Hixson, L.L. Biehl, C.S.T. Daughtry, B.F. Robinson, and E.R. Stoner. November 1978. Vol. I Agricultural Scene Understanding. Final Report: Principal Investigator D.A. Landgrebe. LARS Contract Report 112678. Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana. 106 p.

Results of four investigations, all related to agricultural remote sensing are described. The four tasks are: (A) Analysis of Agronomic and Spectral Data for Physical Understanding, (B) Field Measurements Data Management, (C) Multicrop Supporting Field Research, and (D) Determining the Climatic and Genetic Effects on the Relationships Between Multispectral Reflectance and Physical-Chemical Properties of Soils.

A. The Analysis of Agronomic-Spectral Data report describes the results of analyses of LACIE Field Research Data, including the relationships of agronomic and reflectance characteristics of wheat canopies, effect of cultural and environmental factors on reflectance properties of wheat, and discrimination of wheat and other crops as a function of wavelength band selection and acquisition date.

B. The Field Measurements Data Management report describes field research data base developed at LARS including the development of graphical and statistical analysis software, data processing software, and distribution of data.

C. The Multicrop Supporting Field Research report describes the measurements of spectral characteristics of corn and soybeans and development of a multispectral data acquisition system for field research.

D. The fourth report describes the objectives, experimental approach, and initial results of a study of the relationships between the reflectance and physical-chemical properties of over 400 different soils

Bauer, M.E., L.F. Silva, R.M. Hoffer and M.F. Baumgardner. 1977. Agricultural Scene Understanding. Final Report. Principal Investigator D.A. Landgrebe. LARS Contract Report 112677, The Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana. 173 p.

Results of four investigations, all related to agricultural remote sensing are described. The four tasks are: (A) LACIE Field Measurements, (B) Thermal Band Canopy Modeling, (C) Forestry Applications Project, and (D) Soil Classification and Survey.

A. The LACIE Field Measurements project report describes the rationale for the experiment, the data acquisition, processing, and storage/retrieval by LARS. Results of the sensor correlation and data verification studies are discussed, along with the rationale and procedures for calibration of reflectance measurements. Analytical results of initial analyses relating spectral and agronomic measurements are described. The report concludes with recommendations for future field measurements investigations.

B. The Thermal Band Canopy Modeling results demonstrate the relationship between geometric parameters of wheat canopies, environmental variables, and radiance temperature.

C. The Forestry Application Project report descr bes investigations of (1) the acceptability of Landsat area estimates as inputs to forest inventory, (2) definition of an efficient and cost effective method of developing optimal Landsat training statistics for mapping forest cover, and (3) a comparison of five different classification techniques in terms of cost, accuracy, and output products.

D. The Soil Classification and Survey report describes the results of (1) field experiments relating spectral reflectance measurements to dark and light soils at two surface moisture levels and two amounts of surface residue, and (2) classification for soil survey of multiple dates of Landsat data covering the same scene.

Colwell, J.E. 1974. Grass Canopy Bidirectional Spectral Reflectance. Proc. of the 9th Int. Symp. on Remote Sensing of Environ. v. 2:1061-1085.

The green, red, and near infrared bidirectional reflectance of 'grass' canopies was studied both theoretically and empirically, in order to determine the feasibility of using remote sensing techniques to assess the standing biomass of grasslands. The investigation showed that the optimum spectral bands for remote determination of standing biomass of grasslands vary, depending on such things as the type of vegetation, the range of values of percent vegetation cover present, the soil reflectance, and the look angle and solar zenith angle. No single spectral band can be considered to be effective in all situations.

Coulson, K.L. and D.W. Reynolds. 1971. The Spectral Reflectance of Natural Surfaces. J. Appl. Meterology 10:1285-1295.

The amount of solar energy reflected from various soils and types of vegetation has been measured as a function of sun elevation in six different wavelength ranges in the ultraviolet, visible and near-infrared regions of the spectrum. It is shown that there is a significant dependence of reflectance on both wavelength and elevation of the sun for all surfaces for which measurements were made.

de Boer, T.A., N.J.J. Bunnik, H.W.J. van Kasteren, G.P. de Loor, D. Uenk, and W. Verhoef. 1974. Investigation into the Spectral Signature of Agricultural Crops During their State of Growth. <u>Proc. of the 9th Int. Symp. on Remote Sensing of Environ</u>. v. 2:1441-1455.

The spectral signature from 400 to 2300 nm of 11 crops was determined at different phases of their growth. A fieldspectrometer constructed according to a new principle and developed in the Netherlands, was used. To reduce the number of parameters that affect the directional reflectance of a canopy in its natural environment, the reflectance was measured only perpendicularly to the field surface while using an artificial light source. The purpose of this investigation was to determine, within the available atmospheric windows, the spectral bands in which the optimal differences between the signatures of different crops during their state of growth could be measured. 15 refs.

Dirmhirn, I. and F.D. Eaton. 1975. Some Characteristics of the Albedo of Snow. <u>J. Appl. Meterology</u> 14:375-379.

Spring snowcovers exhibit a substantial contribution of a specular component to their reflection of solar radiation. This anisotropy can be measured with radiometers with small aperture, here with a TIROS radiometer. Indicatrices thus determined are dependent on solar angle. They are of importance for interpreting albedo values and for reducing air- or spaceborne reflectance data taken under distinct nadir angles.

Duggin, M.J. Likely effects of solar elevation on the quantification of changes in vegetation with maturity using sequential LANDSAT imagery. Appl. Optics 16 (March 1977), 521-523.

Recent work has shown that green biomass can be related to ratio functions of the radiance detected by the Landsat scanner in bands 7 and 5. The vernal advancement and retrogradation (green wave effect) may also be be observed from studies of these radiance ratios. The effect of the sun's angle on reflectance properties has so far not been allowed for in studies of sequential images, although a correction of irradiance to a reference sun angle has been made in some cases.
The reflectance factor values and their dependence on solar elevation for each bandpass were found to differ with variety. In general, MSS 7 showed a stronger sun angle dependence than MSS 5. For a change in solar zenith angle from 30 degrees to 60 degrees, the MSS7/MSS5 ratio varied from 25 % to 50%.

Earing, D.G. and J.A. Smith. 1966. Data Compilation of Target and Background Characteristics, Target Signature Analysis Center: Data Compilation. The University of Michigan, prepared for Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio, AD 489 968.

Eaton, F.D. and I. Dirmhirn. 1979. Reflected Irradiance Indicatrices of Natural Surfaces and their Effect on Albedo. Appl. Optics 18(7):994-1008.

The indicatrices of solar radiation reflected from characteristic natural surfaces were measured with a Nimbus Medium Resolution Radiometer (MRIR) 3 m above the ground. Results indicated that areas such as salt and alkali flats had only small deviations from isotropic reflections, while others such as sparsely vegetated areas had substantial deviations. The indicatrices were strongly dependent on the sun angle; thus a daily variation was found for most features. Typical indicatrices, normalized to nadir angle of zero degrees, are presented along with their impacts on measured albedo, which varies with solar angle. Our results can (1) improve surface albedo considerations using space-generated data, and (2) serve as a more realistic lower boundary condition for atmospheric transfer determinations based on space data.

Egbert Dwight D. and Fawwaz T. Ulaby. 1972. Effect of Angles on Reflectivity. Photogrammetric Engineering. Volume XXXVIII, No. 6. Pp. 556-564.

In planning remote sensing missions with multiband photography in the visible and near-infrared regions, few investigators have ready access to the spectral information needed to choose the appropriate filter combinations. A technique has been developed by which one may pre-test to determine the optimum filter combinations and the feasibility of such a multiband mission. The test provides multispectral reflectivity curves not only for the targets or categories to identified, but also for those backgrounds against which they are usually encountered. The procedure incorporates a method for determining spectral reflectance as a function of solar altitude, incidence look angle, and azimuth look angle. This angular dependence of reflectivity can be significant and might be used as an aid in detecting certain targets. It was found that for one target-background pair (asphalt and grass) the contrast ratio can range from 2:1 to 0.5:1 under different angle conditions.

Fuller, S.P. and W.R. Rouse. 1979. Spectral Reflectance Changes Accompanying a Post-Fire Recovery Sequence in a Subartic Spruce Lichen Woodland. Remote Sensing of Envir. 8:11-23.

A sequence of burned surfaces aged 0, 1, 2, 25 and 80 years was investigated regarding changes in the spectral distribution of reflected light. Controls were introduced to isolate diurnal and seasonal effects. The results show gradually increasing reflectance with increasing age of burn. With the establishment of vegetation a new set of absorption and reflectance criteria are established substantially altering the spectral characteristics. The apparent effect of a mature forest canopy is ambiguous. Diffuse and overcast conditions reduce the reflectance for all surfaces. Further work is suggested to reinforce results for surfaces with low sampling replication.

Kalma, J.D. and R. Badham. 1972. The Radiation Balance of a Tropical Pasture, I. The Reflection of Short-wave Radiation. Agric. Meteorol. 10:251-259.

Kanemasu, E.T. 1974. Seasonal Canopy Reflectance Patterns of Wheat, Sorghum, and Soybean. Remote Sensing of Environment 3:43-47.

Reflectance characteristics of agronomic crops are of major importance in the energy exchanges of a surface. In addition, unique reflectance patterns may be an aid in crop identification by means of remote sensing. Our study suggests that the ratio of the reflectances of the 545-nm to the 655-nm wavebands provides information about the viewed surface regardless of the crop. The reflectance ratio is less than unity early and late in the growing season. For all crops studied, the ratio closely followed crop growth and development and appeared to be more desirable than the near-infrared reflectance as an index of growth.

Kimes, D. S., J. A. Smith, and K. J. Ranson. 1979. Interpreting Vegetation Reflectance Measurements as a Function of Solar Zenith Angle. NASA Technical Memorandum 80320. NASA Goddard Space Flight Center. 29 p. (Also submitted to Photog. Eng. & Rem. Sens.)

An understanding of the behavior of vegetation canopy reflectance as a function of solar zenith angle is important to several remote sensing applications. Spectral hemispherical-conical reflectances of a nadir looking sensor were taken throughout the day of a lodgepole pine and two grass canopies. Mathematical simulations of both spectral hemispherical-conical and bi-hemispherical reflectances were performed for two theoretical canopies of contrasting geometric structure. These results and comparisons with literature studies showed a great amount of variability of vegetation canopy reflectances as a function of solar zentih angle. Explanations for this variability are discussed and recommendations for further measurements are proposed.

Kondratiev, K. Y. Z., F. Mironova, and A. N. Otto. 1964. Spectral Albedo of Natural Surfaces. Pure and Appl. Geophysics 59:207-216.

Summary – The short description of the field distance installation for measuring spectral albedo as relation of semi-spherical fluxes of reflected and incoming radiation is made. Data on the measurements of spectral albedo in the wavelength range from 450 to 950 mμ for different natural surfaces are given.

Large Area Crop Inventory Experiment (LACIE). Crop Spectra from LACIE Field Measurements. NASA. Lyndon B. Johnson Space Center, Houston, Texas 77058. March 1978. LACIE-00469, JSC-13734.

The LACIE Field Measurements project has acquired and assembled one of the most comprehensive data sets for agricultural remote sensing research. The purpose of this document is to briefly describe the data sets and to introduce potential investigators to the spectral data through a series of examples illustrating major sources of variation in the reflectance of wheat and several of its confusion crops.

Requests for further information or data should be addressed to:

Chief, Earth Observations Division
Mail Code SF
NASA - Johnson Space Center
Houston, Texas 77058

Middleton, W.E.K. and A.G. Mungall. 1952. The Luminous Directional Reflectance of Snow. Journal of the Optical Society of America 42(8):572-579.

By means of a specially constructed portable goniophotometer the directional reflectance of numerous surfaces of snow was measured during the winter of 1951–1952. While some samples reflected more nearly diffusely than others, all showed much specular reflection at high angles of incidence. An approximate theory of the specular reflection is given and its results compared with experiment. The experimental fact that the angle of maximum reflectance is greater than the angle of incidence is explained by the theory.

Monteith, J. L. and G. Szeicz. 1961. The Radiation Balance of Bare Soil and Vegetation. Quart. J. Roy. Meteor. Soc. 87: 159-170.

Incoming short-wave radiation S, reflected short-wave radiation αS and net radiation R were measured over bare soil and crops from 1957 to 1959, and net long-wave radiation (L) was deduced from

$$R = (1 - \alpha) S - L$$

For grass, α increased from 0·23 at solar elevation 60° to 0·28 at 20° with daily mean 0·26. For bare soil, the corresponding increase was from 0·16 to 0·19 with mean 0·17. In mid-June, L for bare soil decreased from − 0·1 cal cm^{-2} min^{-1} during the night to − 0·4 cal cm^{-2} min^{-1} in the early afternoon. For long grass, in August, the corresponding change was from − 0·05 to − 0·22 cal cm^{-2} min^{-1}. Under clear skies the incoming long-wave component varied much less than the outgoing component, and net flux L was closely related to surface temperature.

With a 'heating coefficient' $\beta = - dL/dR$, the observed linear dependence of R on S in the absence of cloud may be expressed as

$$R = S(1 - \alpha)/(1 - \beta) - L_0$$

where, formally, $R = L_0$ when $S = 0$. For grass, sugar beet and potatoes, β lay between 0·15 and 0·22 with a variation which may depend on wind speed rather than on crop. The value for dry bare soil was higher (0·41) because there was greater surface heating.

Measurements under clear skies and over grass at Cambridge and Kew agree well with Rothamsted values (β = 0·22, L_0 = − 5·9 cal cm^{-2} hr^{-1}). Over Nebraska prairie, β = 0·25, L_0 = − 4·5 cal cm^{-2} hr^{-1} from selected observations during Projects Great Plains and Prairie grass.

Oliver, R. F., J. K. Berry, and J. A. Smith. 1975. A Portable Instrument for Measuring Apparent Directional Reflectance. Opt. Eng. 14(3):244-7.

A portable battery-powered spectroradiometer has been constructed for the measurement of the apparent directional reflectance of natural targets. A silicon detector that is tripod mounted and positioned to monitor a horizontally oriented reference panel determines the target irradiance. A second detector for measurement of target radiance is mounted on the tripod swivel head. Electronic switching provides alternate detector references for the determination of apparent directional reflectance. Snap-on interference filters allow measurement in desired spectral bands. Equipment calibration procedures are discussed and typical experimental radiation data are given (12 Refs).

Rao, V.R., E.J. Brach, and A.R. Mack. 1979. Bidirectional Reflectance of Crops and the Soil Contribution. Remote Sensing of Envir. 8:115-125.

Spectra of cereals, grasses, and corn were measured repeatedly from preflowering to early maturity. The bidirectional and angular aspects were more pronounced for a standing crop such as cereals (oats) than for a clipped sod. The contribution of the soil to the total radiance and the amount of the total radiance were reduced by a greater percentage of ground cover. The effect of angular scattering on radiance decreased with maturity.

Smith, J.A., J.K. Berry, and F. Heimes. 1975. Signature Extension for Sun Angle. EOD, NASA, JSC, NAS 9-14467, Final Report.

This is the second volume in a two-volume final report series for Project NAS 9-14467 sponsored by the Earth Observations Division, NASA/JSC. This report series summarizes the work covered between the period November 15, 1974, and November 14, 1975. The objectives of the project were to evaluate the LACIE II table look-up approach to sun-angle correction. Canopy reflectance modeling was employed as a technique for evaluating sun-angle signature extension.

Volume I presents the multiplicative and additive coefficient matrices for a linear sun-angle correction approach. These coefficient tables are calculated using either measured empirical canopy reflectance functions or model derived data. These values are then incorporated into an atmospheric radiation transfer model. The dependence of the coefficient matrices on crop stage, crop type, and canopy directional reflectance variations is reviewed. Finally, a method for inferring leaf area index, an intrinsic scene characteristic, from canopy reflectance is discussed.

Volume II presents the basic data and computer programs used in the study. A brief review of the radiometric and geometric data collection procedures is also given. In particular, two recent methods developed by the investigators for determining plant geometry are discussed. These include the Fourier diffraction and multiple view angle approach. The data compilation consists of canopy reflectance, constituent reflectance, Leaf-Area-Indices, and leaf slope distributions for four wheat crop development stages at Garden City, Kansas.

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Steiner, D. and T. Cuterman 1966. Russian Data on Spectral Reflectance of Vegetation, Soil and Rock Types. University of Zurich, Switzerland. Final Technical Report.

Tucker, C.J., J.H. Elgin, Jr., and J.E. McMurtrey, III. 1979. Relationship of Red and Photographic Infrared Spectral Radiances to Alfalfa Biomass, Forage Water Content, Percentage Canopy Cover, and Severity of Drought Stress. NASA Technical Memorandum 80272, NASA/Goddard Space Flight Center, Greenbelt, Maryland. 14 p. (Also submitted to Remote Sensing of Envir.)

Red and photographic infrared spectral data were collected using a hand-held radiometer for two cuttings of alfalfa. Significant linear and non-linear correlation coefficients were found between the spectral variables and plant height, biomass, forage water content, and estimated canopy cover for the earlier alfalfa cutting. The alfalfa of later cutting experienced a period of severe drought stress which limited growth. The spectral variables were found to be highly correlated with the estimated drought scores for this alfalfa cutting.

Tucker, C.J., B.N. Holben, J.H. Elgin, Jr., and J.E. McMurtrey, III. 1979. The Relationship of Red and Photographic Infrared Spectral Data to Grain Yield Variation Within a Winter Wheat Field. NASA Technical Memorandum 80318, NASA/Goddard Space Flight Center, Greenbelt, Maryland. 22 p.
(Also submitted to Photog. Eng. & Rem. Sens.)

Two-band hand-held radiometer data from a winter wheat field, collected on 21 dates during the spring growing season, were correlated with within field final grain yield. Significant linear relationships were found between various combinations of the red and photographic infrared radiance data collected and the grain yield. The spectral data explained approximately 65% of the within field grain yield variation. This variation in grain yield could not be explained using meteorological data as these were similar for all areas of the wheat field. Most importantly, data collected early in the spring were highly correlated with grain yield; a five-week time window existed from stem elongation through antheses in which the spectral data were most highly correlated with grain yield; and manifestations of wheat canopy water stress were readily apparent in the spectral data.

Verhoef, W., and N. J. J. Bunnik. 1976. The Spectral Directional Reflectance of Row Crops. Part 1: Consequences of Non-Lambertian Behavior for Automatic Classification. Part 2: Measurements on Wheat and Simulations by Means of a Reflectance Model for Row Crops. Tech. Rept. No. NIWARS-PUBL-35. Netherlands Interdepartmental Working Group on the Application of Remote Sensing, Delft.

Abstract: The one-layer Suits model for canopy reflectance was applied to simulate a multispectral scanning flight over an agricultural area. Non-Lambertian behavior and misclassification were studied on the basis of unprocessed and preprocessed data from the reflectance simulations. A new experimental model for the calculation of the directional reflectance of row crops, based on the one-layer Suits model, is presented. This model was applied to simulate measurements of the spectral directional reflectance on mechanically sowed wheat at several growth stages in the summer of 1974. In general, input and output data of both model and field data agree well. Specular reflection at leaves, not incorporated in the present model, appears to be a significant factor for crop reflectance.

II. MEASUREMENTS

C. PLATFORM (AIRCRAFT AND SATELLITE)

16 references

Brennan, B. 1969. Bidirectional Reflectance Measurements From an Aircraft Over Natural Earth Surfaces. Tech. Rept. No. NASA-IM-X-63564; X-622-69-216. National Aeronautics and Space Admin. Goddard Space Flight Center, Greenbelt, MD.

Brennan, B. and W.R. Bandeen. 1970. Anisotropic Reflectance Characteristics of Natural Earth Surfaces. Appl. Optics 9(2):405-412.

The patterns of reflection of solar radiation from cloud, water, and land surfaces were measured with an aircraft-borne medium resolution radiometer. Reflectances in the 0.2–4.0-μ and 0.55–0.85-μ portions of the electromagnetic spectrum were investigated. Results indicate that the reflectance characteristics of most of the surface types measured are anisotropic. The anisotropy is dependent on the type of surface and the angles of incidence and reflection. In general, the anisotropy increases with increasing solar zenith angle. Clouds and forests show similar reflectance patterns, with forward and backward scattering peaks. Ocean surfaces yield a pattern similar to those of the clouds and forests but with an additional peak which is associated with sun glitter. Reflectances measured in the 0.2–4.0-μ band are generally lower than those in the 0.55–0.85-μ band under cloudy conditions. Anisotropy and spectral bandwidth should be accounted for when computing the albedo of the earth from narrow field-of-view measurements from satellites; otherwise, large errors may be expected to occur.

Coulson, Kinsell L. 1966. Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance. Applied Optics 5(6):905.

Measurements of the reflecting and polarizing properties of various soils, sands, and vegetation in the visible and near-ir spectral regions show that dark surfaces polarize the reflected radiation strongly while highly reflecting surfaces have relatively weak polarizing properties. In general, the reflectance of natural surfaces increases, and the degree of polarization of the reflected radiation decreases, with increasing wavelength and increasing angle of incidence. There is little or no evidence of specular reflection from the surfaces for which measurements were made. Introduction of the reflection data into the equation of radiative transfer for clear and slightly turbid models of the earth's atmosphere shows that the upward radiation that would be incident on a high-altitude aircraft or satellite would be dominated by surface-reflected radiation for the red and near-ir regions over highly reflecting surfaces such as deserts, whereas atmospheric scattering is most important for short wavelengths and dark surfaces. Because of polarization effects, atmospheric transmission of optical contrasts is better in one orthogonal intensity component than the other, the difference being sufficient to merit polarizing optics in reconnaissance instrumentation under certain conditions.

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Duggin, M.J. 1974. On the Natural Limitations of Target Differentiation by Means of Spectral Discrimination Techniques. Proc. of the 9th Int. Symp. on Remote Sensing of Environ. v. 1:499-515.

The paper describes work directed at determining the minimum differences in detected target radiances necessary to exceed noise at the detector. This is caused by atmospheric fluctuations across the scene and by variations in directional reflectance across the target surface. Only when detected radiance differences exceed this noise can terrain classification be unambiguous. For the atmospheric variations which measured and for two typical target radiance values which lie within the range measured, the minimum target radiance difference between single pixels in each of two targets must exceed 20% of the smaller reflected radiance value for meaningful target differentiation of pairs of pixels.

Gushchin, A.N., S.G. Slutskaya, and B.I. Shkurskii. 1977. Investigation of the Spatial Structure of Terrestrial Luminance Fields. Sov. J. Opt. Technol. 44(6):327-330.

The autocorrelation functions and histograms of the one-dimensional luminance distributions of certain terrain and cloud types are obtained and approximated in the 0.5–1.1 and 0.3–11.5 μm spectral intervals for observations at altitudes of 2000–5000 m with a ground resolution of 20–50 m.

Hauth, F.F. and J.A. Weinman. 1969. Investigation of Clouds Above Snow Surfaces Utilizing Radiation Measurements Obtained from Nimbus II Satellite. <u>Rem. Sens. Environ</u>. 1(1):7-11.

Bidirectional reflectance of solar radiation as function of scattering angles from snow and cloud surfaces is found to differ markedly; variation of bidirectional reflectance with scattering angle depends on cloud thickness; infrared temperature data obtained from same region are used in conjunction with these observations to provide information on characteristics of clouds located above snow surfaces; Nimbus II Medium Resolution Data are used to illustrate how such data provide information on clouds above snow surfaces. 9 refs.

Hoffer, R.M. and Staff. 1974. An Interdisciplinary Analysis of Colorado Rocky Mountain Environments Using ADP Techniques. Final Report. LARS/Purdue University. Contract No. NAS5-21880.

This report describes the significant results of a two year interdisciplinary study involving the use of computer-aided analysis techniques applied to ERTS, MSS data collected over rugged mountainous terrain in southwestern and central Colorado. These results involve five specific areas of research, including: 1) Ecological Inventory, with emphasis on the utilization of ERTS data and computer-aided analysis techniques for forest cover mapping and acreage estimates; the results also include a cost analysis; 2) Hydrological Features Survey involving the capability for utilizing ERTS to monitor the change in snow cover and inventory water bodies; 3) Geomorphological Features Survey, with a discussion on the utilization of ERTS data in combination with ancillary information; 4) Interpretation Techniques, discussing the concepts of modeling topographic relief in order to be able to develop better analysis procedures; and 5) Data Collection Platform, a review of the operations of a DCP under adverse climatic conditions.

A section is devoted to a large number of specific results and conclusions of significance, and recommendations for future earth observational systems.

Kriebel, K.T. (1974), The spectral reflectance of a vegetated surface. Part 1: Method and application, <u>Contr. Atm. Phys</u>. 47, 14

Summary: A method is presented to compute the spectral bidirectional reflectance distribution function from the reflected and incoming radiation field with consideration of the spectral sky radiation. This method is applied to a vegetated homogeneous surface. With an eight channel radiometer the angular distribution of the spectral radiation field of a savannah near Tsumeb, Southwestafrica, is measured in the spectral range from 0.4 μm to 2.2 μm by means of an airplane.

The spectral bidirectional reflectance distribution function and the spectral albedo of the savannah are determined. The anisotropy of the bidirectional reflectance distribution function is mostly due to shading effects at the surface. Generally the sky radiation cannot be neglected in relation to the sun radiation. If the sky radiation is distinctly smaller than the sun radiation, the assumption of isotropic sky radiation is justified whereby the determination of the bidirectional reflectance distribution function becomes simple.

Kriebel, K.T. 1976. On the Variability of the Reflected Radiation Field Due to Differing Distributions of the Irradiation. <u>Remote Sensing Environ.</u> 4:257-264.

The directional reflected radiation of natural surfaces may change even if nothing save the distribution of the irradiation over the hemisphere varies. This is due to the angular anisotropy of the reflection properties of natural surfaces. The quantitative determination of this effect for four different vegetated surfaces is the aim of this investigation. In this paper, results for the first of the four surfaces, a savannah, are shown. The directional reflected radiation may change by ± 1% per degree change of the solar zenith angle and by ± 1% per 6% change of the spectral atmospheric turbidity factor at 0.52 μm.

Kriebel, K.T. 1978. Average Variability of the Radiation Reflected by Vegetated Surfaces due to Differing Irradiations. Remote Sensing of Environ. 7:81-83.

The average variability of the reflected radiation field due to differing distributions of the irradiation in case of a savannah was given in a previous paper. In this paper, equivalent results are given for three more surfaces: bog, pasture land, and coniferous forest. Because the results are rather similar, mean values for vegetated surfaces can be derived. They indicate a change of the reflected radiance by ± 1% per degree change of the solar zenith angle and per 10% change of the optical depth of the atmosphere.

Kriebel, K.T. 1978. Measured spectral bidirectional reflection properties of four vegetated surfaces. Appl. Optics 17(2):253-259.

Spectral bidirectional reflectance values are presented at the 0.52-μm wavelength based on measured values of the radiation field of four vegetated surfaces: savannah, bog, pasture land, and coniferous forest, which cover a wide range of natural vegetated canopies. The results are given as examples of the full set of bidirectional reflectance values which consists of data at seven wavelengths between 0.43 μm and 2.20 μm for each of the four surfaces. (From July 1977, the full set of data is available from the author on request.) The data may be applied for calculations of the radiative transfer in the atmosphere with realistic ground properties instead of isotropic albedo values.

V.V. Salomonson (1966), Anisotropy of reflected solar radiation from various surfaces as measured with an aircraft-mounted radiometer. <u>Proc. 4th Symp. Remote Sensing Environ.</u>, University of Michigan. p. 393.

In the past few years, research has been done with satellite-mounted radiometers to determine terrestrial albedos and planetary heat balance. In these studies the reflection of the solar radiation was assumed to be independent of wavelength and isotropic. Using these assumptions, the satellite-determined values of planetary albedo have been found to be consistently low. In an effort toward resolving this discrepancy, the NIMBUS medium resolution radiometer has been mounted on a Piper Twin Comanche and used to measure the anisotropy of reflected solar radiation from various surfaces. By flying over a surface using a prescribed flight pattern and the scanning characteristics of the radiometer, the variations in the reflected radiation in different directions, radiometer zenith angles, and solar zenith angles have been measured. The results show strong forward scattering over stratus clouds at a large solar zenith angle. Backscattering predominates over a grassland surface at a large solar zenith angle. The ratio of averaged observed reflectance to minimum observed reflectance varies from 1.09 to 1.40 depending on the bandpass and the reflecting surface.

Salomonson, V.V. and W.E. Marlatt (1968), <u>J. Appl. Meteorol.</u> 7, 475-483. Anisotropic Solar Reflectance over White Sand, Snow and Stratus Clouds.

Integrated [illegible] reflectances and relative anisotropy were measured over stratus clouds, snow [illegible] types of sand using the Nimbus I-3 medium resolution radiometer (MRIR) and a [illegible] radiometer mounted on a Piper Twin Comanche. Reflectances in the 0.2–4.0 [illegible] 0.55–0.85 [illegible] portions of the solar spectrum were investigated. Eight flights were completed in different geographic areas over stratus clouds of varying thicknesses. Three flights were made over snow [illegible] different locations and five flights were made over white sand found in the White Sands National Monument, N. Mex.

The greatest anisotropy in scattered radiation was observed over stratus clouds. This anisotropy was composed of strong forward scattering and less pronounced backscattering. The anisotropy observed in the radiation reflected from snow was primarily due to specular reflection in the forward direction. Reflection back toward the sun was the predominant feature in the reflectance distributions observed over gypsum sand. The results demonstrate the interaction of the spectral reflectivity of the surface, the spectral response of the instrument, and the spectral character of the energy impinging upon the reflecting surface.

Salomonson, V.V. and W.E. Marlatt. 1971. Airborne Measurements of Reflected Solar Radiation. Remote Sensing Environ. 2, 1-8.

In a study contributing to better satellite determinations of the earth-atmosphere radiative heat budget, measurements of the directional variation in reflected solar radiation over soils and vegetation have been made using an aircraftborne scanning radiometer with a field of view of 50 mrad. Bidirectional reflectances were observed in two portions of the solar spectrum (0.2–4.0 μ and 0.55–0.85 μ) at times when the solar zenith angle was between 55° and 80°. Flights were made over a dry desert lake bed devoid of vegetation, a soil surface covered by short grasses, and a densely vegetated surface. The results show anisotropy in the reflected solar radiation over each of the surfaces. The largest bidirectional reflectances were observed in the backscattering directions (at angles greater than 90° to the direction of the incident radiation). Over the dry desert lake bed, higher bidirectional reflectances were observed in the 0.55–0.85 μ bandpass than in the 0.2–4.0 μ bandpass; however, over the densely vegetated surface the larger reflectances were observed in the 0.2–4.0 μ bandpass. The overall results support suggestions that crop identification and radiation budget determinations are possible over large agricultural areas through appropriate spectroradiometric measurements from satellites.

Schutt, J.B. 1977. Understanding Bidirectional Reflectance and Transmission for Space Applications. IN: Standardization in Spectrophotometry and Luminescence Measurements. K. D. Mielenz, R. A. Velapoldi, and R. Mavrodineanu (Eds). Nat. Bur. Standards Publ, Washington, D. C. 2:87-93.

Applications for optical diffusers in space projects are presented which include the functions of reflection, transmittance, and collection. These modes encompass such diverse uses as temperature regulation and ozone concentration monitors. Discussed is the cooperative aspect of diffuse reflectance and environmental stability. Magnesium oxide, sodium chloride and barium sulphate are evaluated in some detail. The importance of scene scattering behavior to modeling the earth's radiation budget and in determining thermal inertias of the earth's surface are discussed. Finally, work in the area of canopy reflectance modeling is reviewed with verification data included whenever available.

Smith, J. A., T.L. Lin and K.J. Ranson. 1979. The Lambertian Assumption and Landsat Data. Submitted to Photog. Eng. Rem. Sens.

Analysis of terrain geometric effects on the optical scattering properties of *Pinus ponderosa* as measured by the Landsat multispectral scanner has been performed. A mountainous study site in Colorado was utilized in which effective view angles between the surface normal vector and the zenith satellite sensor angle ranged between 0 and 45°. Effective illumination angles between the surface normal vector and the sun at image acquisition ranged between 30 and 80°.

Seventy-six sample points of similar cover density and type were selected within the study site. Topographic slope, aspect, and calculated incidence and exitance angles were merged with the multispectral Landsat response for MSS bands 4, 5, 6, and 7. Regression analysis was applied to the data in order to fit a generalized photometric function. The slope of the regression line may be compared to the expected value for Lambertian scattering and a test of significance performed. At the 95% significance level, the Lambertian assumption for ponderosa pine Landsat responses was rejected.

III. APPLICATIONS AND TECHNIQUES

14 references

Coulson, K. L. and H. Jacobowitz. 1972. Proposed Calibration Target for the Visible Channel of a Satellite Radiometer. Tech. Rept. NOAA TR NESS 62. U.S. National Oceanic and Atmospheric Admin., Nat. Environ. Satellite Serv., Wash., D. C. 27 pp.

ABSTRACT. A method is proposed for calibrating the visible channel of a satellite radiometer from orbit by using a sunlit area on the earth's surface as a calibration target. For a highly reflective surface and solar elevations of 30° or greater, the dominant component of the intensity of radiation directed outward from the top of the atmosphere is attributable to incident solar radiation which is transmitted directly downward through the atmosphere, reflected from the surface, and transmitted directly back out through the atmosphere. Aside from the solar constant, the only parameters that must be known to determine this dominant intensity component are the directional reflectance of the surface and the optical thickness of the atmosphere. Both can be measured directly with the proposed instrumentation. The intensity components arising from diffuse transmission or backscatter can be determined by measuring the global flux incident at the surface and applying radiative transfer theory for realistic models of the turbid atmosphere over the calibration site. A single filter instrument for the measurement of the global flux is suggested. A preliminary survey indicates that the white gypsum sand of the White Sands National Monument, N. Mex., may be the most suitable calibration target within the United States. If a suitable surface observation station could be established, another very attractive possibility is the Solar de Uyuni, a large salt flat at an altitude of 12,000 feet in Bolivia.

Egbert, D.D. 1977. A Practical Method for Correcting Bidirectional Reflectance Variations. <u>Symp. Proc. Machine Processing of Remotely Sensed Data</u> 178-189.

The purpose of the investigation described here was to analyze angular bidirectional reflectance variations and test the hypothesis that first order variations could be described from a consideration of shadows created by surface perturbations. The results reported here demonstrate the validity of this approach, and while it is not suitable for calculating absolute spectral reflectance characteristics, the development of such a model was not the objective of the investigation since other models already exist for these calculations. Instead, a model was needed which can make relative angular corrections to bidirectional reflectance measurements independent of the details of surface geometry. The theoretical model derived in this investigation from an analysis of shadow formation is such a model.

Holben, B. N. and C. O. Justice. 1979. Evaluation and Modeling of the Topographic Effect on the Spectral Response from Nadir Pointing Sensors. NASA Technical Memorandum 80305. NASA Goddard Space Flight Center, Greenbelt, Maryland 20771. 19 p.

A field experiment using a hand-held radiometer was designed and conducted to assess a simple theoretical incidence model for simulating the topographic effect of a uniform sand surface. Seven data sets were taken to compare effects of solar elevation and azimuth encountered at different times of year. Analysis of these data showed considerable variation in radiance values for different slope angles and aspects and that these values varied considerably with changes in solar elevation and azimuth.
A model to simulate Landsat sensor response was applied to two subsets of the field data to establish the magnitude of the topographic effect on satellite data. A range of 35 pixel values was obtained for the high solar elevation data subset, showing that a wide range of pixel values can be associated with one cover type due solely to variations in slope angle and aspect.

Horn, B. K. P. and Brett L. Bachman. 1978. Using Synthetic Images to Register Real Images with Surface Models. <u>Communications of the ACM</u> 21(11):914.

A number of image analysis tasks can benefit from registration of the image with a model of the surface being imaged. Automatic navigation using visible light or radar images requires exact alignment of such images with digital terrain models. In addition, automatic classification of terrain, using satellite imagery, requires such alignment to deal correctly with the effects of varying sun angle and surface slope. Even inspection techniques for certain industrial parts may be improved by this means.

We achieve the required alignment by matching the real image with a synthetic image obtained from a surface model and known positions of the light sources. The synthetic image intensity is calculated using the reflectance map, a convenient way of describing surface reflection as a function of surface gradient. We illustrate the technique using LANDSAT images and digital terrain models.

Key Words and Phrases: image registration, synthetic images, surface models, automatic hill shading, digital terrain models, image transformation, image matching, shaded images

CR Categories: 3.63, 3.11, 3.14, 8.2, 3.83

Jackson, R. D., R. J. Reginato, P. J. Pinter, Jr., and S. B. Idso. 1979. Plant Canopy Information Extraction from Composite Scene Reflectance of Row Crops. Accepted for Publication in Applied Optics.

As an aid in the interpretation of remotely sensed data from row crops with incomplete canopies, a model was developed that allowed the calculation of the fractions of sunlit soil, shaded soil, sunlit vegetation, and shaded vegetation for each resolution element in a scan of a remote sensor for a given set of conditions (plant cover, plant height/width ratio, row spacing, row orientation, time of day, day of year, latitude, and size of resolution element). Using measured representative reflectances of the four surfaces, composite reflectances were calculated as a function of view angle. Also, representative temperatures for each surface were used to simulate composite temperatures viewed by an infrared scanner. With composite reflectances and temperatures known as a function of view angle, ways were explored to extract plant cover and plant temperature data from the composite data.

Kauth, R.J. and G.S. Thomas. 1976. The Tasselled Cap--A Graphic Description of Spectral Temporal Development of Agricultural Crops as seen by Landsat. Proc. Symp. on June 29-July, 1976. Purdue University, West Lafayette, Indiana. Machine Processing of Remote Sensing Data.

Multispectral scanner data are potentially useful in a variety of remote sensing applications. Large-area surveys of earth resources carried out by automated recognition processing of these data are particularly important. However, the practical realization of such surveys is limited by a variability in the scanner signals that results in improper recognition of the data. This paper discusses ways by which some of this variability can be removed from the data by preprocessing with resultant improvements in recognition results.

Koepke, P. and K.T. Kriebel. 1978. Influence of Measured Reflection Properties of Vegetated Surfaces on Atmospheric Radiance and its Polarization. Appl. Optics 17(2):260-264.

Based on measured values of the spectral bidirectional reflection functions of four vegetated surfaces, the influence of their angular anisotropy on the upward and downward emerging radiance and its polarization is calculated. By means of a realistic model of the atmosphere and with the assumption of completely depolarizing reflection properties of the surfaces, results are obtained in dependence of wavelength and solar zenith angle. The angular anisotropy influences considerably the upward emerging radiance. On the degree of polarization and on the downward emerging radiance the anisotropy has negligible to small influence. Due to the angular anisotropy of the reflection properties the spectral albedo depends strongly on the solar zenith angle. This influences upward and downward radiance as well as its degree of polarization. Therefore, for the interpretation of radiation measurements, those spectral albedo values should be used which correspond to the respective solar zenith angle. This is essential especially at longer wavelengths where vegetated surfaces have high spectral albedos.

Lambeck, Peter F. 1977. Signature Extension Preprocessing for Landsat MSS Data. Final Report, NASA CR-ERIM 122700-32-F. Environmental Research Institute of Michigan. 74 p.

Current signature extension preprocessing techniques which have been developed or investigated at ERIM are presented. The discussion covers the underlying theory for the preprocessing, the development of haze correction algorithms (specifically XSTAR and XBAR), the development of an automatic screening procedure to detect garbled data, clouds, snow, cloud shadows, and water in Landsat MSS data, results from tests of the preprocessing performance, some analyses of soil color effects in Landsat data, and conclusions and recommendations for future developments in preprocessing.

Malila, W.A., R.H. Hieber, and J. E. Sarno. 1974. Analysis of Multispectral Signatures and Investigation of Multi-aspect Remote Sensing Techniques. ERIM 190100-27-T, Environmental Research Institute of Michigan. 112 p.

Two major aspects of remote sensing with multispectral scanners (MSS) are investigated. The first, multispectral signature analysis, includes the effects on classification performance of systematic variations found in the average signals received from various ground covers as well as the prediction of these variations with theoretical models of physical processes. The foremost effects studied are those associated with the time of day airborne MSS data are collected. Six data collection runs made over the same flight line in a period of five hours are analyzed; it is found that the time span significantly affects classification performance. Variations associated with scan angle also are studied.

The second major topic of discussion is multi-aspect remote sensing, a new concept in remote sensing with scanners. Here, data are collected on multiple passes by a scanner that can be tilted to scan forward of the aircraft at different angles on different passes. The use of such spatially registered data to achieve improved classification of agricultural scenes is investigated and found promising. Also considered are the possibilities of extracting from multi-aspect data, information on the condition of corn canopies and the stand characteristics of forests.

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Malila, W.A., R.H. Hieber, and R.C. Cicone. 1975. Studies of Recognition with Multitemporal Remote Sensor Data. Final Report, ERIM 109600-19-F. Environmental Research Institute of Michigan, The University of Michigan, Ann Arbor, Michigan. 99 p.

Characteristics of multitemporal data and their use in recognition processing was investigated. Principal emphasis was on satellite data collected by the LANDSAT multispectral scanner (MSS) and on temporal changes throughout a growing season. The motivation for the studies was LACIE . Since multitemporal LACIE data were not available for the study, CITARS data were used instead, with corn and soybeans as the major crops and a small amount of winter wheat.

Three studies are reported. The first is of the effects of spatial misregistration on recognition performance with multitemporal data. A new capability to compute probabilities of detection and false alarm was developed and used with simulated distributions for misregistered pixels . A two-time-period case was simulated in this initial study. Wheat detection was found to be degraded and false alarms increased by misregistration effects. Recommendations are made for continued analysis of this problem in LACIE applications .

The second study was of multitemporal signature characteristics and multitemporal recognition processing and was made to gain insights into problems associated with this approach and possible improvements. Empirical and simulation studies of signatures showed substantial variability within some cover classes. Recognition performance with one multitemporal data set did show marked improvements over results from single-time data, especially for crop proportion estimates for full sections of test data. Further investigations on LACIE data sets are recommended. Also recommended are measurements of wheat reflectance characteristics.

Thirdly, time of day effects on multispectral recognition performance were studied in aircraft MSS data. Degradations associated with the passage of time were found to be substantial but largely correctable by signature adjustments based on average signals over the scene. Corrections based only on theoretical sun-angle corrections were inferior. Incidental to the reported study, calculations showed that the thermal channel was preferred for single-time recognition.

Nalepka, R. F. and Jon D. Erickson. 1974. Investigation Related to Multispectral Imaging Systems. Final Report, NASA CRERIM 190100-46-F, Environmental Research Institute of Michigan. 188 p.

This report contains a summary of technical progress made during a five-year research program directed toward the development of operational information systems based on multispectral sensing and the use of these systems in earth-resource survey applications. Efforts were undertaken during this program to: (1) improve the basic understanding of the many facets of multispectral remote sensing, (2) develop methods for improving the accuracy of information generated by remote sensing systems, (3) improve the efficiency of data processing and information extraction techniques to enhance the cost-effectiveness of remote sensing systems, (4) investigate additional problems having potential remote sensing solutions, and (5) apply the existing and developing technology for specific users and document and transfer that technology to the remote sensing community.

Ranson, K.J., J. Kramer, J. Kirchner, and J.A. Smith. 1978. Evaluation of Illumination and Terrain Geometry Effects on Spectral Response in Mountain Terrain. Final Report. Volume II. Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service, Cooperative Agreement 16-741-CA. 84 p.

An extensive analysis of terrain geometric effects on the optical scattering properties of natural resource scene in mountainous terrain has been performed. Spectral reflectance measurements were obtained for lodgepole pine, *Pinus contorta*, ponderosa pine, *Pinus ponderosa*, Russian olive, *Elaeagnus angustifolia*, grass species, *Agropyron sp.*, and *Bromus sp.*, and snow. Sensor platforms included ground-based measurements using aerial tramways, aircraft radiometric observations, and satellite (Landsat) measurements. A wide range of effective view and source illumination angles were recorded for the various target/sensor combinations.

Regression analyses and photometric plots were made from the data in order to test the Lambertian assumption for the various material types. In addition a process-oriented radiative transfer model was applied to the data. This model was also used to evaluate initial effects of background topographic variations.

Results of this study indicate that, particularly in the chlorophyll absorption band all materials exhibit non-Lambertian behavior for effective zenith sensor or source angles greater than 60 degrees, but that for effective angles less than 40 degrees, the Lambertian assumption may be valid. For stable atmospheric conditions and constant phase angle the Minnaert relationship may be applied to

quantify scene radiance properties. The canopy reflectance model was found to follow the general trends of the field measurements but overestimates infrared response. In order to adequately model topographic influences or spectral response, canopy density variations must be included.

Smith, J.A. and R.E. Oliver. 1974. Effects of Changing Canopy Directional Reflectance on Feature Selection. <u>Appl. Optics</u> 13(7):1599-1604.

A Monte Carlo model was used to predict the mean apparent directional reflectance of a simulated plant canopy and the covariance for seven wavelength channels in the visible portion of the spectrum. The non-Lambertian spectral response from *Bouteloua gracilis* canopies possessing two plant cover densities was simulated for two solar positions. The calculated spectral signatures as a function of look angle were then analyzed using the divergence criteria to select the best two wavelength channels for discrimination. These calculations indicate that different combinations of wavelength channels are appropriate for various sensor look angles, that target signatures have greater statistical separation for some scan angles than others, and that these effects are time varying.

Struve, H., W.E. Grabau, and H.W. West. 1977. Acquisition of Terrain Information using LANDSAT Multispectral Data. Report 1. Correction of LANDSAT Multispectral Data for Extrinsic Effects. Technical Report M-77-2. Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 50 p.

This report provides an analytical capability for correcting the spectral data, as received by Landsat, to radiance values at ground level. Variations in the radiance values as influenced by atmospheric effects, terrain geometry, and shadows are coupled together to form a single equation that converts the radiance values of images obtained at different times to a common datum.

IV. BIDIRECTIONAL REFLECTANCE - DEFINITIONS

7 references

Judd, D.B. 1967. Terms, Definitions, and Symbols in Reflectometry. Journal of the Optical Society of America 57(4):445-452

Angular conditions of incidence are described as hemispherical, conical, or directional; the same adjectives are used to describe the angular conditions of collection. This classification of angular conditions leads to nine kinds of reflectance; symbols for them are proposed in which 2π, g, and θ_0, ϕ_0 refer to hemispherical, conical, and directional incidence, 2π, g', and θ_r, ϕ_r refer to the corresponding kinds of collection. Use of the perfectly reflecting mirror and of the perfectly reflecting diffuser as reference standards in reflectometry is discussed. Three of the nine reflectance ratios, specimen to perfect diffuser, in which the collection is directional have already been named radiance [luminance] factor. It is proposed to differentiate them by angular condition of incidence. It is also proposed to name the other six ratios: reflectance factor qualified by the same adjectives identifying the type of incidence and collection as are used for reflectance. The interrelationships of these 18 concepts are shown both by formulas for computing one from another and by diagrams indicating the process (integration, summation, averaging, equality, reflectance of perfect diffuser, and reciprocity) by which values of one concept may be computed from those of another.

Kasten, F., and Raschke, E. (1974), Reflection and transmission terminology by analogy with scattering, Appl. Opt. 13, 460.

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Nicodemus, F.E. 1964. Directional Reflectance and Emissivity of an Opaque Surface. Technical memo. Rept. No. EDL-G266. Sylvania Electronic Systems-West Mountain View Calif. Electronic Defense Labs. 29 p.

Abstract: Concepts, terminology, and symbols are presented for specifying and relating directional variations in reflectance and emissivity of an opaque surface element. Their relationship to more familiar concepts, including those of perfectly diffuse and specular reflectance, is given, and they are applied to illustrative examples. It is shown that, when the usual reciprocity relationship holds, the reflectance for a ray incident on an opaque surface element is related by Kirchhoff's Law to the emissivity of that element for a ray emitted along the same line in the opposite sense. (Author)

Nicodemus, F. E. 1970. Reflectance Nomenclature and Directional Reflectance and Emissivity. Appl. Optics 9 (6):1474-1475.

Nicodemus, F. E. 1976. Comment on 'Current definitions of Reflectance'. J. Opt. Soc. Am. 66(3):283-5.

In their recent paper, Spencer and Gaston (See Ibid., Vol. 65, P. 1129 (1975)) based their conclusions regarding one of the definitions on limitations which do not in fact exist. The delta-function form of the bidirectional reflectance-distribution function (BRDF) can represent a "glint" in any direction and is not limited only to the case where theta/sub v/=theta/sub I/ and PSI/sub v/=PSI/sub/I +or-PI(RAD). The conceptual advantage of a completely general BRDF is considered in relation to the whole continuum of directional distributions which occur between the two extremes of only specular "spikes" and totally diffuse reflection (6 Refs).

Nicodemus, F.E., J.C. Richmond, J.J. Hsia, I.W. Ginsberg, and T. Limperis. 1977. Geometrical Considerations and Nomenclature for Reflectance. Natl. Bur. Stand. Monogr. No. 160. pp. 1-52.

A unified approach to the specification of reflectance, in terms of both incident- and reflected-beam geometry, is presented. Nomenclature to facilitate this approach is proposed. Under specified conditions SEM DASHS including uniform irradiance, a uniform, isotropic, plane surface, and allowance for edge effects due to sub-surface scattering SEM DASHS the geometrical reflecting properties of a reflecting surface are readily characterized or specified in terms of the bidirectional reflectance-distribution function (BRDF). The BRDF is a derivative, a distribution function, relating the irradiance incident from one given direction to its contribution to the reflected radiance in another direction. Nomenclature (concepts, terms, symbols, and units) for categorizing and specifying reflectance quantities for a variety of different beam configurations (both incident and reflected beams, is described, and all are defined and interrelated in terms of the BRDF. 38 refs.

Self-study Manual on Optical Radiation Measurements. Part 1 - Concepts, Chapters 4 and 5. F.E. Nicodemus, Editor. NBS Technical Note 910-2, U.S. Dept. of Commerce/National Bureau of Standards. 105 p. 1978.

BIDIRECTIONAL REFLECTANCE STUDIES

LITERATURE REVIEW

2.7 SYNTHESIS

OCTOBER, 1979

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I. INTRODUCTION

This is the second part of a two part literature review of bidirectional reflectance studies relevant to the Multispectral Resource Sampler, the MRS. Part I contains an annotated bibliography of the actual references reviewed and a brief discussion of the general theme of the references. The material was subdivided into a discussion of: 1) Theory and Models; 2) Measurements - further broken down into laboratory, field, and platform; 3) Applications and Techniques, and; 4) Definitions. The purpose of this report, Part II, is to provide a narrative commentary or synthesis of our current knowledge base as evidenced from the literature review.

The theoretical base for predicting scene bidirectional reflectance behavior for a variety of earth surface features resides in the radiative transfer equations. During the past 70 years significant advances have been made by both astrophysicists and atmospheric scientists in applying, modifying, and experimenting with solution techniques for these equations. These studies have been concerned with steller or planetary atmospheres, including the earth's atmosphere. There has been tremendous diversity and ingenuity evidenced by the various investigations in adapting radiative transfer techniques to various specialized cases. In contrast, when one searches for a similar breadth of activities which focuses on the application of radiative transfer theory to the study of such earth features as forest canopies and crops, there is almost an embarrassing lack of activity. Probably, this is a recognition of the difficulty of specifying the appropriate phase function in both a sufficient and

tractable manner and further, performing the necessary measurements to determine the phase function. That is, in addition to the difficult mathematical problem of solving systems of non-linear integro-differential equations, there is a physics or biological problem of characterizing phase functions for individual trees, groups of trees, and so forth which **themselves are of distributions of such scattering elements as** needles, twigs, understory and so forth. There is then the additional problem of performing the actual measurements required to characterize the geometric and optical properties of the scatterers. Traditional field methods for doing this are totally inappropriate and time consuming. Thus, there is a wealth of material developed by atmospheric scientists and others which can be drawn upon to assist us in solving the mathematical radiative transfer problem for earth surface features. However, the problem of determining the appropriate phase functions seems to have discouraged most investigators from pursuing the problem further.

The models that have been developed fall into two categories. These I will term subcomponent models or canopy or scene models. Subcomponent models have been applied to individual leaves, or collections of mineral surfaces. These models are generally either patterned after stacked plates or Kubelka-Munk approaches. Ray-tracing techniques have also been applied. Two major efforts have been made at developing canopy or scene reflectance models. These are the Suits model (1972) and the SRVC model of Smith and Oliver (1972). The bulk of Section II is concerned with an overview of these two models particularly from the perspective of radiative transfer theory. Both models apply to homogeneous plane-parallel media. The models, while useful in themselves, are really only first steps in a development of a broader theoretical base for

predicting scene reflectance. The models were developed in 1972; there has been extensive application of the models to various situations, particularly agriculture. Bunnik and co-workers (1974) being the most aggressive. However, there remains the nagging question of why there hasn't been an onslaught of other modeling approaches in the ensuing eight years. Section II concludes a few comments on other modeling efforts.

As noted in the Literature Review, Part I, there are numerous measurements of the directional reflectance properties of natural materials. However, considerable confusion and variability arises in the interpretation of the measurements and in the techniques used to obtain them. Except in very general terms, we find it difficult to accurately synthesize the various measurements as a whole. Consequently, we decided to beg the question a bit. What we include in Section III is a description of definitions appropriate to the various experiments. We then refer to a fairly large Appendix which contains approximately 45 figures which have been gleaned from the literature to illustrate the experimental trends. These supporting figures have been broken down into source and view angle effects, phase angle effects on polarization, application of ratio techniques, and angular considerations for enhancing classification. For each group of figures we have been careful to include a brief summary paragraph of the investigator's results and indicate the type of reflectance measurement reported.

Finally Section IV concludes with a brief list of recommendations for future research appropriate to developing bidirectional reflectance characterization of scenes.

II. THEORY AND MODELS

As was indicated in the Literature Review, Part I, of this report series there are currently two major optical reflectance models which appear to be relevant to the MRS. These are the Suits model (1972) and the SRVC model of Smith and Oliver (1972). The purpose of this section is to give a perspective of the significance and limitations of these two approaches and identify key unsolved problems where further work is required. A brief overview discussion of radiative transfer theory is first given in order to set the context within which the Smith and Suits models were developed. Next the specific formulation of the Suits model is given, followed by a discussion of the important properties of the SRVC approach. Finally, a discussion of related model efforts is given.

. ``'IATIVE TRANSFER THEORY

Radiative transfer theory is concerned with the quantitative description of the transfer of radiant energy through media which absorb, scatter, or emit radiant energy. It is primarily a macroscopic analysis of the interaction of radiant energy with matter in that it describes the observed phenomena of light scattering, absorption, and polarization effects but without regard to classical electromagnetic theory. Rather, bulk properties of the media, such as a volume scatter coefficient (e.g., the phase function) are defined. The media can either be thought of as a continuum or as a collection of discrete scatterers. The theory assumes that the individual scatterers behave incoherently; thus,

diffraction effects are not included. The formulation of the radiative transfer equations is deceptively simple. The basic starting point is essentially the principle of energy conservation.

Consider an arbitrarily bounded medium and focus on the steady-state, monochromatic radiance along any path ds. The change in radiance along this path is the difference between that attenuated (absorbed or scattered) out of the beam and the intensity scattered into the beam. Let the incident beam of cross section dA be along the direction defined by Θ, ϕ. If n is the number density of scatterers in the volume element under consideration; σ the scattering or absorption along ds, then:

$$\frac{dI(s;\theta,\phi)}{ds} = -\sigma n I(s;\theta,\phi) + nJ(s;\theta,\phi) \qquad (1)$$

where:

$I(S;\Theta,\phi)$ = the radiance at s in the direction θ, ϕ.

$J(S;\Theta,\phi)$ = the radiance at s scattered into the beam from all directions.

The probability that radiance at s in a direction Θ', ϕ' will be scattered into a solid angle about Θ,ϕ is given by the phase function, $P(S: \Theta, \phi; \Theta', \phi')$. Thus, J is given by integrating the total intensity field along all directions (paths) by the phase function.

$$J(s;\mu,\phi) = \frac{1}{4\pi}\int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\phi' \, I(s;\mu',\phi') \, P(s;\mu,\phi;\mu',\phi') \tag{2}$$

where the symbol $\mu = \cos\theta$ has been introduced.

In order to include polarization effects, these expressions must be modified to include a vector radiance function, I, with four components corresponding to the Stokes parameters, and a phase matrix. Polarization effects may be important for some classes of materials, e.g., vegetation canopies with waxy leaves, e.g., pine needles, rhododendron, holly, often produce a strong specular reflection or glare. If this glare is polarized, then polarization filters, such as proposed on the MRS could act to reduce this source of noise. Conversely, as Egan, et al. (1968, 1970) suggest, discrimination potential may exist in the asymmetric depolarization effects as a function of view angle. However, current existing canopy models ignore polarization and it will not be discussed further.

The general solution to the integro-differential equation (1) may formally be given by:

$$\begin{aligned} I(s;\mu,\phi) &= I(s_0;\mu,\phi)\, e^{-T(s,s_0)} \\ &+ \int_{s_0}^{s} n\, J(s';\mu,\phi)\, e^{-T(s,s')}\, ds' \end{aligned} \tag{3}$$

where:

$$T(s,s_0) = \int_{s_0}^{s} n\,\sigma\, ds$$

However, this solution for I along one path, s, depends on integrating J which itself is an integral of the intensity, I, over all possible paths, s'. Thus, in reality, the general radiative transfer problem reduces to the problem of solving an infinite set of coupled integro-differential equations.

For an arbitrarily bounded medium with phase functions which themselves can vary with position within the medium, e.g., as in a row crop, this is not a trivial problem. In fact, there is no known solution.

Alternatively, simpler problems must be formulated by imposing various abstractions on the medium. These abstractions may include the shape or boundary of the medium and the form of the phase functions. The phase functions, in turn, depend upon the optical scattering properties of the elements within the medium and on geometrical factors. Both Smith and Suits initially approach the problem by assuming multi-layered homogeneous plane-parallel media for vegetative canopies (the infinite plane-terrain models referred to in the Literature Review, Part I).

For the special case of plane-parallel media, the radiative transfer equations may be re-expressed as (Chandrasekhar, 1960):

$$\mu \frac{dI(\tau;\mu,\phi)}{d\tau} = I(\tau;\mu,\phi) - \mathcal{J}(\tau;\mu,\phi) \qquad (1')$$

where:

$dz = \mu ds$ $\qquad$ z = vertical direction

$d\tau = -\sigma dz$ $\qquad$ τ = optical depth

and $\mathcal{J} = \dfrac{J}{\sigma}$ $\qquad$ J = source function

Similarly, equation (3) becomes:

$$I(\tau; \pm\mu, \phi) = I(\tau_0; \pm\mu, \phi)\, e^{-(\tau - \tau_0)/\mu} + \frac{1}{\mu} \int_{\tau_0}^{\tau} \mathcal{J}(\tau'; \pm\mu, \phi)\, e^{-(\tau - \tau')/\mu}\, d\tau' \tag{3'}$$

Basically, this equation states that the upwelling (downwelling) radiance at optical depth, τ , is a result of the upwelling (downwelling) attenuated radiance at τ_0 plus that scattered into the beam along the path between τ and τ_0.

Again, it should be noted that the source function depends upon the total radiance field along all paths.

$$\mathcal{J}(\tau; \pm\mu, \phi) = \frac{1}{4\pi} \int_{-1}^{1} d\mu' \int_0^{2\pi} d\phi'\, I(\tau; \pm\mu', \phi') \times P(s: \pm\mu, \phi; \mu', \phi') \tag{2'}$$

The plane-parallel case is much more tractable, particularly, for selected choices of the phase function. One approach, utilized by Suits, makes an initial guess for the total radiance field, I, by first factoring

I into an upwelling (+Z) completely diffuse field, a completely down-welling (-Z) diffuse field, and an attentuated downwelling specular field. This three-stream approximation to the radiance field is obtained by solving the resulting simplified radiative transfer equations (1'), which in fact are the Duntley equations (an expansion of the Kubelka-Murk equations). Given an initial guess for I, the source function, $\mathcal{J}$, may be calculated from (2'), and subsequently, an updated estimate of I along a particular direction made be determined from equation (3'). In principle, iteration should generate a solution to any desired degree of accuracy. In practice, Suits stops at the first iteration. Smith makes a direct attack on the numerical solution of equation (3'), using a random walk procedure.

A second general approach which has proved useful in solving the radiative transfer problem for plane-parallel media is the method of invariant embedding. Essentially, this approach uses several invariance principles ennunciated by Chandrasekhar to derive expressions for the total canopy bidirectional scattering (reflectance) and transmission functions, the S and T, parameters introduced by Chandrasekhar.

The essence of the contributions of both Suits and Smith and Oliver, lie in their application of these techniques to multi-layered canopies and in relating the phase functions to biological parameters which can be measured in the field. There are some key differences in the two implementations which will become apparent in the following discussion. It should also be noted that both methods need to be extended in order to apply them to what Holmes (1974) has called structured earth scenes, i.e., heterogeneous mixtures.

B. THE SUITS MODEL

The following discussion is an analysis of a "one layer" Suits model in the context of the general radiative transfer equations (1') through (3'). This approach is not, in fact, the way Suits cast his original development. However, it should be useful in linking his analytical and physical reasoning of canopy radiation interactions to the broader mainstream of radiative transfer theory. A similar discussion of the SRVC model will be given in the next section. It should be noted that Smith and Oliver also did not initiate their analysis with the radiative transfer equations. Extension of these discussions to the multilayered, multicomponent case involve further complications which are best reviewed in the author's original papers.

Consider a canopy with total optical depth, τ_o, layer thickness Z_o, and irradiated by specular (solar) flux at μ_o, ϕ_o. The plane-parallel homogeneous canopy consists of Lambertian scatters with component reflectance, r_c, and component transmittance, τ_c. The background soil reflectance is r_s. We seek to determine $I(0; +\mu, \phi)$, where (μ, ϕ) is the view angle. This is the radiance, L, of the canopy for this view angle. Ratioing this value to the solar irradiance, $I(0; -\mu_o, \phi_o)$ would be a measure of the canopy bidirectional reflectance value for this pair of source and view angles.

Equation (3') becomes:

$$I(0;+\mu,\phi) = L(\mu,\phi) = I(\tau_o;+\mu,\phi)\, e^{\tau_o/\mu} + \frac{1}{\mu}\int_{\tau_o}^{0} J(\tau';+\mu,\phi)\, e^{\tau'/\mu}\, d\tau' \tag{4}$$

The first term of this expression is simply the radiance from the soil surface attenuated through the canopy. As mentioned earlier, the difficulty with the second term is the fact that the source term under the integral depends on the total radiance field at all levels within the canopy. However, if we initially assume that the canopy is totally and <u>uniformly</u> diffusing, that is, when incident radiation interacts with a canopy element, it is converted totally to diffuse flux, we can replace the total radiance field by the sum of three components. These are downward specular flux, downward diffuse flux, and upward diffuse flux.

$$I(\tau, +\mu', \phi') = I(+d, z) + I(-d, z) + I(s, z) \tag{5}$$

Using this as an initial guess in the source integral (2'), we can improve our estimates by iteration. This approximation corresponds to the Duntley approach to calculating the flux, E(+d,z), E(-d,z), and E(s,z). Note that

$$E = \pi L = \pi I \tag{6}$$

The Duntley equations are given by:

$$\frac{dE(+d,z)}{dz} = -a\,E(+d,z) + b\,E(-d,z) + c\,E(s,z)$$

$$\frac{dE(-d,z)}{dz} = a\,E(-d,z) + b\,E(+d,z) - c'\,E(s,z) \tag{7}$$

$$\frac{dE(s,z)}{dz} = d\,E(s,z)$$

where the coefficients were related under suitable assumptions by Suits to canopy geometric concepts. For example,

$$a = n\,\sigma_h\,(1-\tau_c) + n\,\sigma_v\left[1 - \frac{r_c + \tau_c}{2}\right]$$

where n is the number of scatterers per unit volume, and σ_h and σ_v are the average cross sections of horizontal and vertical projections respectively. Equation (7) may be solved for E, equation (6), and subsequently for I, equation (5). What remains to be determined in order to solve for the source terms, equation (2') is the phase function. Suits approximates this quantity by separately calculating phase functions for each of the three radiance terms in equation (5). Canopy geometric terms and the component optical properties are utilized, for example, the first phase function is given by:

$$P(+d:\mu,\phi;\mu',\phi') = n_h\,\sigma_h\,z\,\tau_c + n_v\,\sigma_v\,z\,\frac{\tau_c + r_c}{2}\left(\frac{2}{\pi}\right)\tan\theta$$

Central to the development of the Duntley coefficients and the phase functions is the abstraction of the canopy vegetation elements into horizontal and vertical scattering projections.

The final expression for the initial iteration of the surface radiance is given by the rather formidable expression:

$$L(\mu,\phi) = \frac{1}{\pi}\,r_s\,I(+d,z_0)\,e^{kz_0/\mu} \qquad (8)$$

$$+ \text{ (See next page)}$$

$$\frac{1}{\mu}\int_{z_0}^{0} K\Big\{\Big[n_h\sigma_h z r_c + n_v\sigma_v \frac{r_c+r_c}{2}\left(\frac{2}{\pi}\right)\tan\theta\Big] I(+d,z$$

$$+\Big[n_h\sigma_h r_c z + n_v\sigma_v \frac{r_c+r_c}{2}\left(\frac{2}{\pi}\right)\tan\theta\Big] I(-d,z)$$

$$+\Big[n_h\sigma_h r_c z + n_v\sigma_v \frac{r_c+r_c}{2}\left(\frac{2}{\pi}\right)^2\tan\theta\tan\theta_0\Big]$$

$$I(s,z)\Big\}\,dz$$

where

$$K = n_h\sigma_h + \left(\frac{2}{\pi}\right) n_v\sigma_v \tan\theta$$

These expressions may be integrated in closed form leading to easily implemented computer code. A strong advantage of the Suits model is the relative ease in performing a large number of simulations for various combinations of viewing and illumination geometry, canopy structure parameters, and optical properties of the canopy. In general, good agreement between the model and field experiments has been reported. A potential drawback in the structure of the model is the assumption of horizontal and vertical canopy projections.

C. THE SMITH AND OLIVER SRVC MODEL

The SRVC model treats the canopy as a stratified, three-layered vegetation ensemble of foliage elements superimposed on a reflecting background. Multiple scattering interactions within the volume elements of the layers are controlled by the geometry and optical properties of the individual scatterers. Foliage elements generate multiple diffuse

sources. Each layer can contain up to two types of vegetation elements, which are assumed to be Lambertian scatterers. A key difference from the Suits model that is introduced by the SRVC approach is the utilization of the angular distribution and density of the scatterers, the foliage elements, to calculate the phase function that is utilized in Equation (2'). A second difference is that a direct solution of Equation (3') is instituted. That is, the flux within the canopy is allowed to propagate in discretized θ' ϕ' directions rather than only an upwelling and downwelling vertical direction.

The main feature of the model which allows for this generality is the calculation of the layer phase functions from the angular distribution of the foliage elements and the reflectance and transmission properties of these elements with respect to the discretized θ' ϕ' source directions. A foliage element inclined at an arbitrary orientation with respect to a source direction permits according to the Lambertian response, the scattering by transmission and reflection of the incident flux to upper and lower hemispherical sectors. For each foliage inclination angle represented in the canopy a set of integration limits on the scattered radiation from a scatterer is defined. For a given layer the distribution of flux is then weighted by the frequency distribution of foliage inclinations occurring within the layer.

The model initiates an iterative solution of Equation (3') by using the zeroth order flux above the canopy to generate via the phase function of the first layer the estimated flux in layer one. The estimated flux in layer one is then used together with the phase function for layer

two to calculate the estimated flux in layer two and so forth. Subsequently, reflection from the soil boundary generates upward moving flux, again in a set of discretized θ', ϕ' directions. Processing is continued until all flux levels within layers reach equilibrium values.

The current version of the SRVC model is a Monte Carlo implementation of the above processes. Statistical distributions may be defined for the foliage geometry and optical scattering properties. A major difficulty of the current implementation of the SRVC model is the pooling of the outgoing radiance into theta directions only. That is, outgoing azimuthal directions are averaged. It should be noted, however, that incoming source azimuth directions are included. The SRVC model requires considerable computing time for the Monte Carlo analysis of a canopy.

In principle, however, the SRVC approach is an accurate representation of the radiative transfer processes occurring within a plane-parallel medium. A deterministic version of the model that included outgoing azimuthal dependence would greatly enhance the utility of the SRVC approach.

D. OTHER MODELING EFFORTS

It is obvious from the discussions in Sections B and C that the most serious difficulty in both of the models discussed is the question of their applicability to targets which possess horizontal spatial variations, e.g., row crops.

One major effort to develop a model applicable to this case is the work reported by Verhoef and Bunnik (1976). Basically, the authors attempted to extend the Suits model to the row structure case by assuming:

1. The canopy components are packed in rows with a rectangular cross-section of fixed dimensions.
2. Between rows there is open space only.
3. Within rows a random arrangement of leaves exists.

A detailed geometric analysis of the canopy phase function relative to direct solar flux and canopy row structure is undertaken. Shading is allowed. However, the approximation is made that diffuse flux can be treated as in the Suits model, i.e., plane parallel media. For both direct and diffuse flux, an appropriate view probability function is developed that is consistent with the row structure. The soil contribution is also carefully developed considering the row structure but leads to discontinuous contributions of this component to canopy reflectance.

The row model still incorporates the assumption of vertical and horizontal canopy projections. In evaluating the model the authors describe the treatment of the leaf angle distribution as a potential difficulty. The authors further describe the assumption of Lambertian scatterers (i.e., non-specular) as a second difficulty. The row model predicts angular dependency relative to viewing azimuth from plane parallel media models.

Another recent and intriguing effort at developing reflectance models for non-random canopies is briefly described by Welles and Norman (1979). Detailed descriptions and evaluation of this model are not yet available. Briefly, the model considers a canopy to consist of a finite number of regularly-spaced ellipsoids. Within each ellipsoid,

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the foliage is randomly located but possesses a foliage angle distribution. Each foliage element is represented by a flat plate. In fact, th ellipsoids appear to be similar to the canopies of the SRVC approach.

Each point in the finite array of ellipsoids is transformed to an equivalent plane parallel media canopy by choosing a depth in the plant parallel canopy that has the same diffuse penetration probability considering both upward and downwelling radiative flux. Processing is continued until all of the ellipsoid array points have been processed. Norman's track record is good and the model, when published, should provide valuable insights.

Jackson, et al. (1980) describe another example of a row model based on a geometric analysis of the row structure.

As mentioned in the Literature Review,Part I, Egbert (1977) describes a novel analysis of canopy reflectance based on shadows.

III. MEASUREMENTS AND THE BRDF FUNCTION

A. DEFINITIONS

The bidirectional reflectance distribution function, ρ, is defined by the following fundamental equation for the radiance at a point of observation, θ_r, ϕ_r, arising from irradiance distributed over a set of incidence angles, θ_i, ϕ_i:

$$L(\theta_r, \phi_r) = \frac{1}{\pi} \iint \rho(\theta_i, \phi_i; \theta_r, \phi_r) E(\theta_i, \phi_i) \cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i$$

Thus, the BRDF, ρ, which has units of sr^{-1}, describes the scattering of irradiance from source direction θ_i, ϕ_i into the view direction θ_r, ϕ_r. In reality, measurements are taken over finite solid angles, Ω_r. If, for example, the source is also distributed over a finite solid angle, Ω_i, then:

$$L(\Omega_i, \Omega_r) = \frac{1}{\pi} \iint_{\Omega_r} \iint_{\Omega_i} \rho(\theta_i, \phi_i; \theta_r, \phi_r) E(\Omega_i) \cos\theta_i \, d\Omega_i \cdot \cos\theta_r \, d\Omega_r$$

Measurement of $L(\Omega_i, \Omega_r)$ ratioed to the response from a Lambertian Barium Sulfate panel would be termed the bidirectional reflectance factor, a dimensionless quantity. (More specifically, it would be the conical-conical or biconical reflectance factor referring to the conical viewing and illumination geometry). While the reflectance factor must always be less than or equal to 1, the BRDF may assume very large values. For specular reflection, for example, it is represented by a Dirac delta function. Probably, the most common field measurement of reflectance is a measurement of the hemispherical-conical reflectance

factor (or perhaps the hemispherical-directional) referring to the restricted view geometry but the integration of irradiance over a hemisphere. In fact, as is evident from the literature review, many investigators believe they are measuring the bidirectional or biconical reflectance factor in this case. However, this approximation is valid only when the direct solar irradiance strongly dominates and diffuse irradiance is negligible. For clear days, this is generally valid near solar noon, perhaps, for solar zenith angles less than 40 degrees. If target materials were Lambertian reflectors, the fact that the radiance in one direction is dependent upon contributions of the irradiance from all possible directions of the hemisphere would present no difficulty. However, it is precisely the deviation from Lambertian scattering which is often of major interest.

Kriebel (1977) has attempted inverting the integral radiance equation to derive the BRDF. An alternative method of correcting for the diffuse irradiance field was tried by Bauer, et al. (1977). Measurements of both the target and reference panel were obtained under total illumination and in a shaded conditions. The investigators rejected the technique as compared to the standard method of ratioing the target radiance to the total irradiance. However, all target reflectances were obtained for a nadir view angle and restricted sun angles.

Other definitions of bidirectional reflectance are evident in the literature. Salomonson and Marlatt (1971) define the term to be the ratio of the radiance measured by the sensor to the effective solar irradiance E^* on a Lambertian surface of unit reflectivity at the top of the atmosphere. Integration of this function over all angles of exitance

is defined by these authors as the directional reflectance. Thus, the term refers to the ratio of the total reflected flux to that incident at a particular solar zenith angle. Just the opposite convention is used by Coulson, et al. (1965) and Oliver, et al. (1975) who reserve the term to what is really the hemispherical-conical reflectance factor. When the radiance measurements are integrated over broad portions of the spectrum, the term albedo is commonly employed.

B. REFERENCE TO APPENDIX

It is evident from the literature review that earth surface features exhibit anisotropy in their reflected radiation patterns, particularly at large zenith view and illumination angles. Polarization effects may be present. Some success with channel ratio techniques for normalizing these effects has been observed. Limited research has been performed relative to the utilization of off-angle measurements for improving classification performance. However, it is predicted that measurements at zero phase angle will be sensitive to leaf color, measurements at approximately 50 degrees zenith - view angle will be independent of canopy architecture, and measurements at approximately 55 degrees zenith view angle may be most sensitive to Leaf-Area-Index changes. The Literature Review, Part I, referenced many of the important papers supporting the general observations above. What is included in the Appendix to this report is a collection of approximately 45 figures and tables which illustrate the magnitude of these observed effects. Each group of figures is preceded by a short discussion of the author's main conclusions. Particular care has been executed to include a reference to the type of reflectance measurement made as discussed in the preceding section.

The Appendix has been organized into four sections to give examples of: A) Source and View Angle Effects on Reflectance; B) Phase Angle Effects on Polarization; C) Applications of Ratio Techniques, and; D) Angular Considerations for Enhancing Classification.

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IV. SUMMARY AND RECOMMENDATIONS

Any sensory system such as the MRS is a record of the radiance emanating from the scene in passing through a turbid medium, the atmosphere. The radiance may be recorded as a function of wave length; polarization characteristics may also be measured. These measurements may be obtained for a given view and illumination geometry or they may be obtained temporally either on a short time frame or a longer phenological time scale. The MRS offers several additional dimensions to radiance measurement capability in that subportions of a large scene may be sampled. This sampling may be done for a variety of measurement geometries and the temporal sampling frequency is greatly increased over previous systems.

Probably the most popular data analysis and information extraction procedures that will be utilized with MRS data will be the mapping of scene elements, based on their radiance measurements, into desired informational classes using the classical techniques of pattern recognition. In addition, particularly in the agricultural arena, the direct mapping of such agronomic variables as Leaf-Area-Index will be attempted through the establishment of correlations between the desired variables and radiance transformation of the radiance such as ratios. These techniques should prove useful, particularly if ancillary information is incorporated, as they have in earlier satellite platforms. However, some difficulties may arise from the variability induced by differing view and illumination geometries.

A second analysis approach may also prove useful in the extraction of information from MRS data. Indeed, the MRS may offer a useful platform for evaluating such techniques. This approach may be termed the indirect sensing of scene parameters based on understanding (models) of the physical radiative interactions with biological elements. This approach is akin to some of the standard techniques employed by atmospheric scientists in the deduction of the aerosol or temperature profiles of the atmosphere from the integrated radiance from a medium.

To fully apply either of these broad information extraction approaches one should have an understanding of the bidirectional surface reflectance function. It is evident from the literature review that significant strides have been made by numerous investigators in obtaining indicative field measurements. Model development has also been initiated. The work which has been done and which is ongoing in the research community suggests several specific research questions which are relevant to the MRS concept. It appears that a carefully planned and directed field measurement program should be implemented for selected earth surface features. A main objective of such an effort would be to insure that adequate supporting field measurements are available to both validate and extend modeling efforts. For this combined approach of modeling and field experiments it would probably be wise to do a few things well rather than many things poorly. Thus, priorities should be established for the kinds of targets to be investigated. These priorities should consider both scientific and national goals. Such an effort that is concerned primarily with radiative transfer characteristics of the scene-atmosphere system

as it is relevant to the MRS concept should also of course, be useful to other research experiments suggested by application or discipline scientists.

Within this context the following five example candidate research tasks are suggested:

1. Establish a high quality field data base appropriate to scene modeling efforts at both the canopy and subcomponent level. In order to accomplish this task reliable procedures must be developed for measuring the bidirectional reflectance distribution function for target materials. Such techniques may need to consider the total directional irradiance field, not just the solar component. Consequently, the referencing of target radiance to a barium sulfate panel may not always be appropriate. Even high quality radiance data by itself is of limited utility without supporting descriptors of the scene. In this regard the various subcomponent and canopy models should prove useful in indicating the required field parameters.
2. Initiate a comprehensive attack on the canopy-level target modeling problem. This effort should include review of standard and recent radiative transfer theory from the mainstream of atmospheric science and developments in neutron transport theory. Such a review should prove valuable in providing potential non-atmospheric science investigators with a background in available numerical solution techniques for the "mathematical" part of the radiative transfer problem. Once investigators have formulated the "physics" of the problem, i.e., various ways of

parameterizing phase functions for surface targets, this review may also assist them in determining whether their abstraction is similar to the "classical" cannonical examples.

Specific modeling tasks which should be initiated in the near future include:

(i) Modify the Suits model to include non-orthogonal projections, at least for the phase function. The ultimate utility of the Suits approach is likely to be limited by the orthogonal assumption, even for homogeneous plane-parallel canopies.

(ii) Modify the Smith and Oliver SRVC model to include viewing azimuth dependencies. Convert the Monte Carlo implementation to a deterministic mode. Make the model "easy" to use by the uninitiated.

(iii) Benchmark the above models on appropriate data sets which will probably require specific field or laboratory experiments. Identify strengths and weaknesses, (breakdowns in assumptions) and recommend improvements. It is likely that the result of this analysis will be guidelines for the design of a new model appropriate for homogeneous plane-parallel media.

Further modeling tasks which should also be initiated in a reasonable time frame include:

(iv) An attack on what Holmes has called the structured earth problem, e.g., models appropriate for row crops, and other mixture "pixels". Bunnik has suggested a

way to modify the Suits approach to handle this case. The SRVC model may lend itself to such cases, particularly at a discrete point level. Jackson has indicated some phenomenological approaches to the problem. The modeling of the mixture pixels from a process-oriented viewpoint, as opposed to a statistical approach, is obviously a difficult problem. It may be that it is solvable only for selected cases; perhaps, by approaches which have not yet been formulated. It is particularly with regard to this problem that a review of radiative transfer theory is suggested.

(v) Include polarization effects in the existing canopy models. A theoretical analysis of selected hypothetical canopies should then lead to predictions which can be verified either in the laboratory or field.

3. Initiate a review of canopy submodels. Carefully defined laboratory experiments similar to the early work of Breece and Holmes should be executed. These results will prove useful for the canopy level models. In addition, the applications of target models to discipline-oriented problems will be improved by linking agronomic variables through the subcomponents to the canopy level.

4. Examine the feasibility of defining new feature sets useful for multispectral, multiaspect, or multi-polarization classification. A systematic review of the impact of surface response variability should prove useful in defining potential preprocessing or normalization algorithms.

5. Examine the impact of a true bidirectional reflectance di..ri-bution function, versus a Lambertian assumption, on atmospheric modeling. The coupling of BRQF models to atmospheric models may require some subtle considerations.

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SYNTHESIS

A. Source and View Angle Effects on Reflectance

B. Phase Angle Effects on Polarization

C. Applications of Ratio Techniques

D. Angular Considerations for Enhancing Classification

A. Source and View Angle Effects on Reflectance

Breece, H.T.(III) and R.A. Holmes. 1971. Bidirectional Scattering Characteristics of Healthy Green Soybean and Corn Leaves in Vivo. Appl. Optics 10(1):119-127.

Study of the bidirectional reflectance of corn and soybean leaves in a laboratory. (Figures 4, 5 and 6) are polar bidirectional scattering distribution functions for live, healthly soybean leaves at incidence angles 0°, 30° and 60°. For wavelengths greater than 750 nm both reflectance and transmittance are more lambertian compared to the highly absorptive smaller wavelengths. Leaf reflectance is more specular than transmittance at strongly absorbing wavelengths.

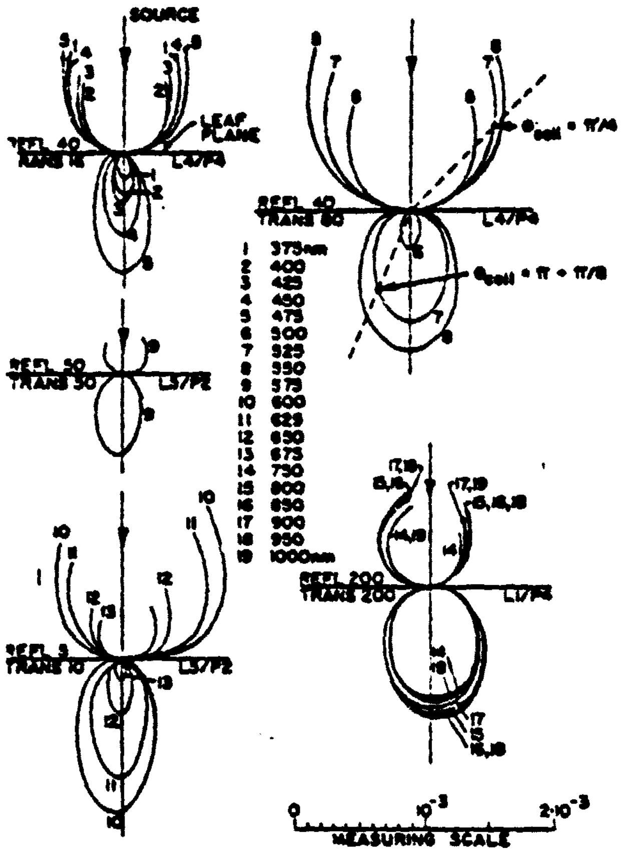

Fig. 4. Polar plots of soybean leaf $\rho'\cos\theta_{cell}$ and $\tau'\cos(\pi - \theta_{cell})$ for top incidence at $\theta_{inc} = 0°$.

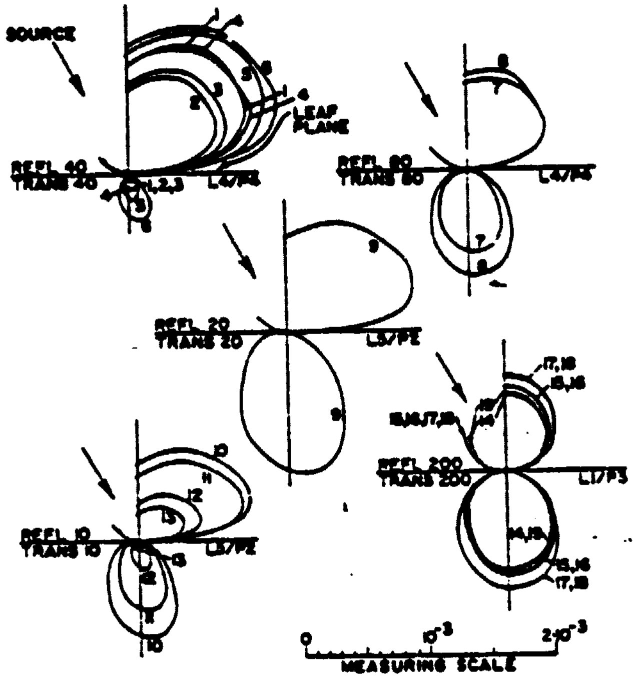

Fig. 5. Polar plots for soybean similar to those of Fig. 4, with identical wavelength code but for top incidence at $\theta_{inc} = 30°$.

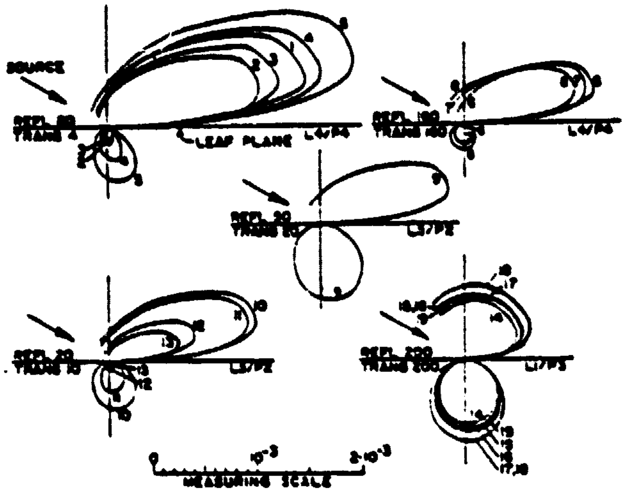

Fig. 6. Polar plots for soybean similar to those of Fig. 4, with identical wavelength code but for top incidence at θ_{inc} = 60°.

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Colwell, J.E. 1974. Grass Canopy Bidirectional Spectral Reflectance. <u>Proc. of the 9th Int. Symp. on Remote Sensing of Environ.</u> v. 2:1061-1085.

In this study of using bidirectional reflectance measurements to assess the standing biomass of grasslands source-sensor angle variations were considered. Table lists the reflectance for solar zenith angles of 20° and 75°. Reflectances are greater at the 20° sun angle for the green, red and IR bands. This trend is reversed for green/red, IR/red and IR/green ratios. The reason given for the lack of normalization in the ratios is the difference in transmission for the three bands and hence differential shadowing (V = vertical LAI, H = Horizontal LAI).

Spectral reflectance changes are complicated by the addition of view angle. In the case of Figure 4 at large look angles canopy reflectance, for two zenith angles, increases with increased zenith angle and at small look angles canopy reflectance decreases with increasing zenith angle.

IR/red reflectance ratios vs. total leaf area index are plotted in Figure 3. Ratioed reflectances differences for Timothy and Oats as a function of biomass are shown in Figure 8.

TABLE 3. EFFECT OF ZENITH ANGLE ON CHANGE IN CANOPY BIDIRECTIONAL SPECTRAL REFLECTANCE FOR A 0° LOOK ANGLE (V/H = 2/1)

			Reflectance			
Zenith Angle	Green	Red	IR	Green/Red	IR/Red	IR/Green
20°	10.2	6.0	34.5	1.7	5.8	3.4
75°	5.4	1.5	25.0	3.6	16.7	4.6

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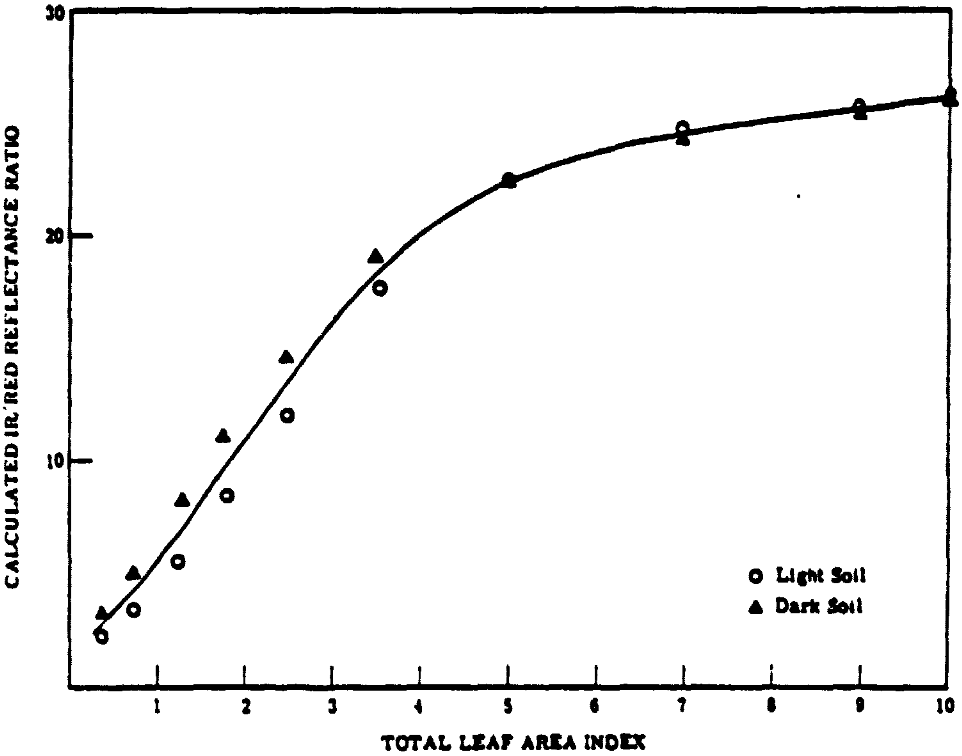

FIGURE 3. CALCULATED RATIO VERSUS TOTAL L.A.I. Look angle, $\phi = 0^{\circ}$, zenith angle, $\theta = 20^{\circ}$.

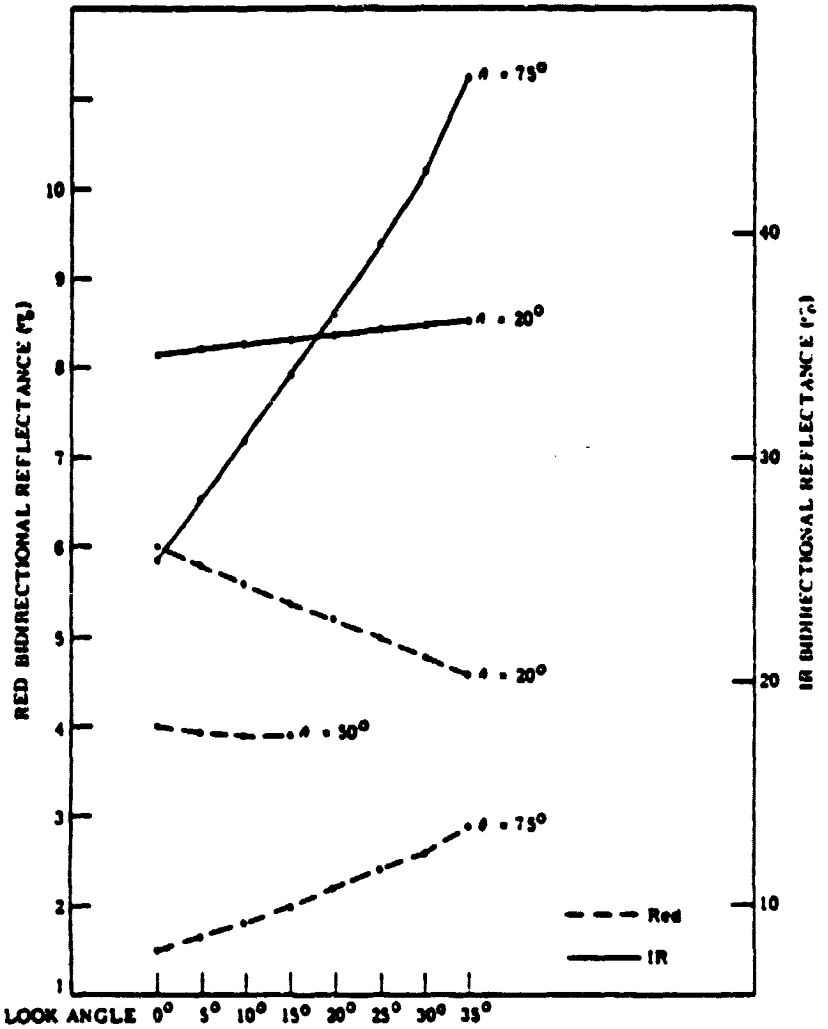

FIGURE 4.
ANGULAR VARIATION IN BIDIRECTIONAL REFLECTANCE AS A FUNCTION OF SOLAR ZENITH ANGLE AND LOOK ANGLE. H = 0.5, V = 1.0, ψ = 0°, light soil.

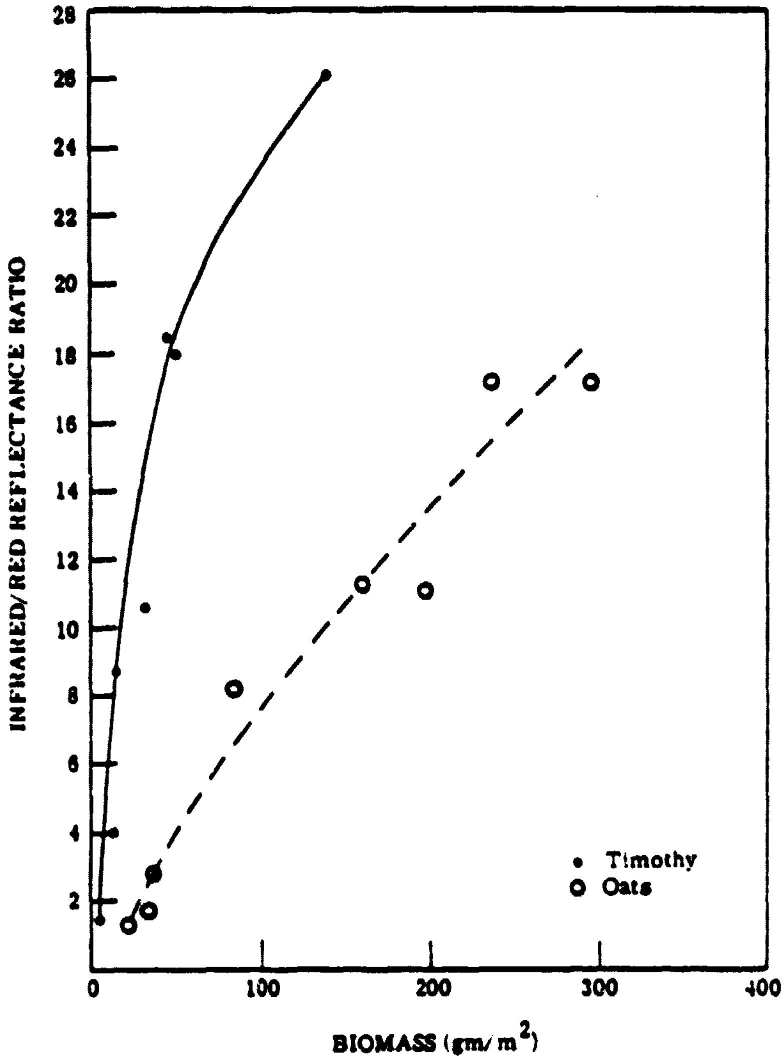

FIGURE 8. INFRARED/RED REFLECTANCE RATIO FOR LIGHT SOIL AND 0° LOOK ANGLE FOR OATS AND TIMOTHY

$\phi = 0°$

Coulson, K.L. 1966. Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance. Appl. Optics 5(6):905-917.

Hemispherical-directional reflectance and polarization measurements were obtained for various sands, soil and vegetation. In general reflectance increases and polarization decreases with increasing wavelength and increasing incidence angle for mineral surfaces. For darker soil surfaces (Figure 4) and green vegetation (Figure 7) the maximum reflectance in the antisource direction is less pronounced than for light-colored sand (Figure 2).

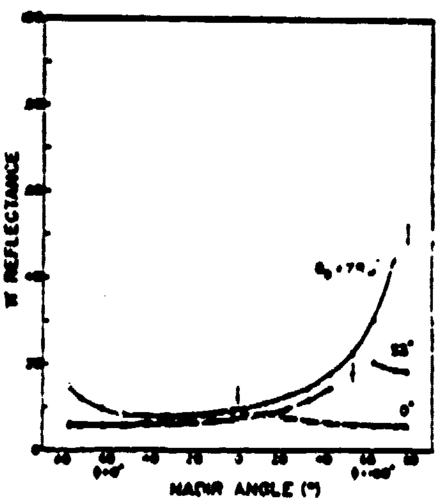

Fig. 4. Directional reflectance of black loam soil at three different angles of incidence (principal plane, λ = 6400 Å).

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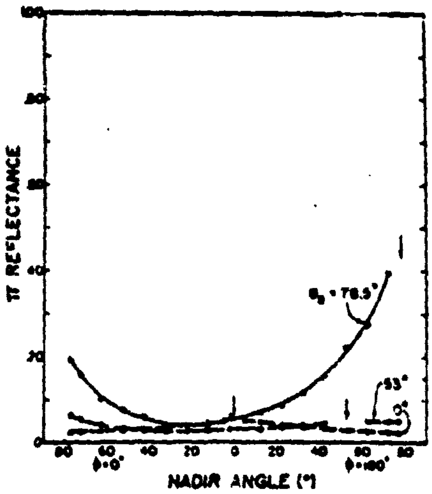

Fig. 7. Directional reflectance of green grass turf at three different angles of incidence (principal plane, λ = 6430 Å).

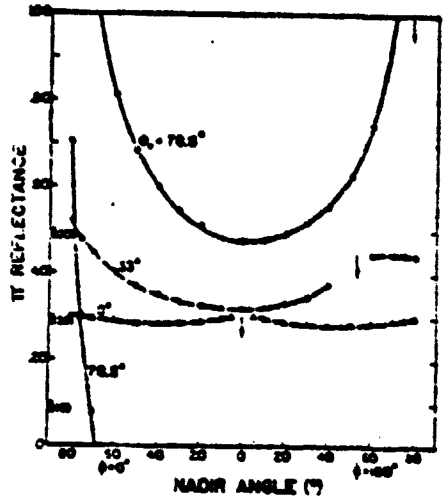

Fig. 2. Directional reflectance of desert sand at three different angles of incidence (principal plane, λ = 6430 Å).

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Coulson, K.L., G.M. Bouricius, and E.L. Gray. 1965. Optical Reflection Properties of Natural Surfaces. J. Geophysical Res. 70(18): 4601-4611.

Measurements of hemispherical-conical reflectance and linear polarization for natural sands and soils are presented for wavelength of 492 nm, 643 nm and 796 nm. Isopleths of directional reflectance (actually hemispherical-conical) of red clay in the 643 nm band indicate maximum values at large view angles. A broad band of minimum values occurs through the 0° - 90° azimuth angle half of the hemisphere. Antisource reflectances are higher (Figure 4). Degree of polarization isopleths of red clay indicate that the phase angle is the dominant parameter due the pattern around the antisource direction (Figure 5).

Directional reflectance of white quartz as a function of view angle and various incident angles show a general increase of reflectance with increasing solar altitude. The maximums occur at the backward direction and the reflectance increases with sun angle at 0° azimuth. Quartz appears to be more lambertian at smaller sun angles. Curves at left with auxillary ordinate show that reflectance at 80° view angle and 0° azimuth is more than three times as great for a sun angle of 78° as that reflected from the standard magnesium oxide surface (Figure 10). Higher polarization values are noted for quartz, however no polarization maximum occurs (Figure 11).

Note: clay is red-opaque, quartz is white-semitransparent.

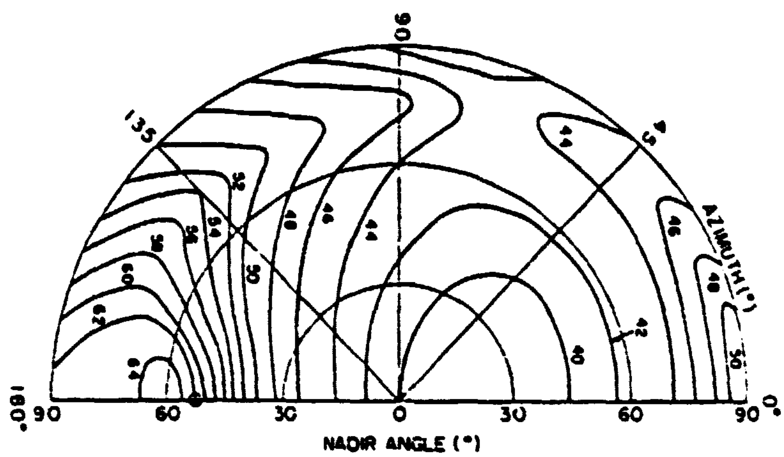

Fig. 4. Isopleths of the directional reflectance ($\pi\rho$) over the outward hemisphere for red clay soil. $\theta_0 = 53°$, $\lambda = 6430$ A. Nadir angle is represented by distance outward from the origin, and azimuth angle is taken with respect to source position. The pattern is symmetrical with respect to the principal plane. The curves have been extrapolated for $\theta > 80°$.

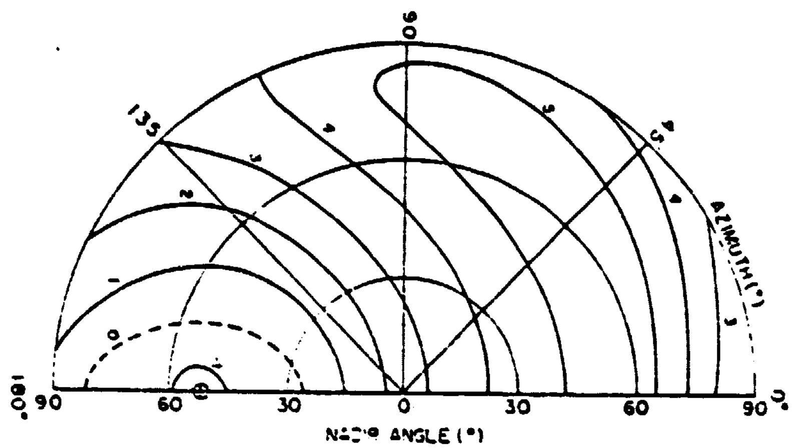

Fig. 5. Isopleths of the degree of polarization of radiation reflected into the outward hemisphere from red clay soil. $\theta_i = 53°$, $\lambda = 6130$ Å.

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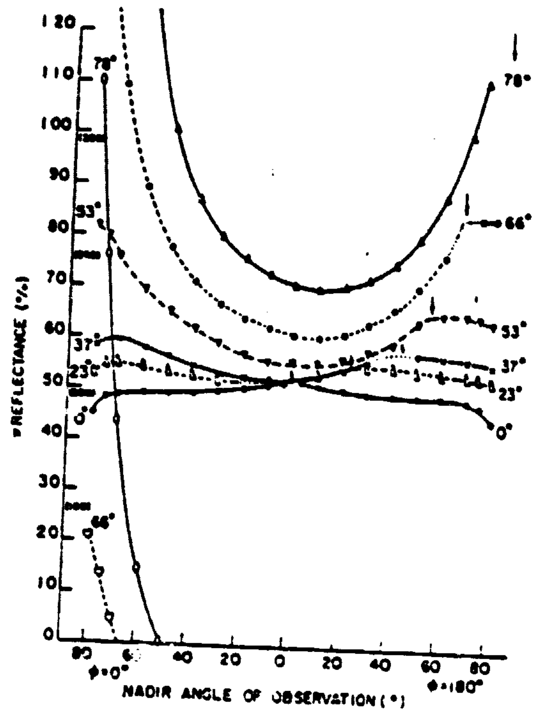

Fig. 10. Directional reflectance of white quartz sand, as a function of nadir angle, for various angles of incidence. $\lambda = 6430$ A, principal plane.

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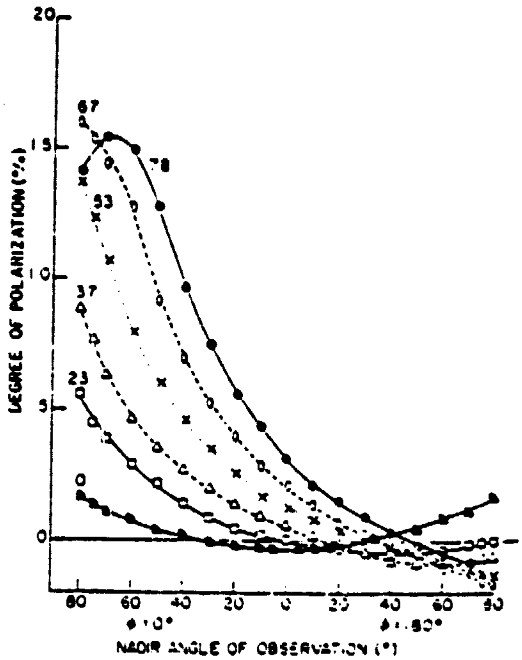

Fig. 11. Degree of polarization of radiation reflected from white quartz sand, as a function of nadir angle, for various angles of incidence. $\lambda =$ 6420 Å, principal plane.

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Coulson, K.L. and D.W. Reynolds. 1971. The Spectral Reflectance of Natural Surfaces. J. Appl. Meteorology 10:1285-1295.

Measurements of bihemispherical reflectances of several natural surfaces. The reflectance of most surfaces reaches a maximum at sun elevations of 10-20°. Surfaces of a complex structure generally show a decrease of reflectance with increasing sun angle. Figure 14 depicts the bihemispherical reflectance of green bluegrass turf at five different wavelengths. It appears that at lower wavelengths the reflectances are nearly lambertian for sun elevations greater than 20°. This pattern holds for most of the surfaces studied.

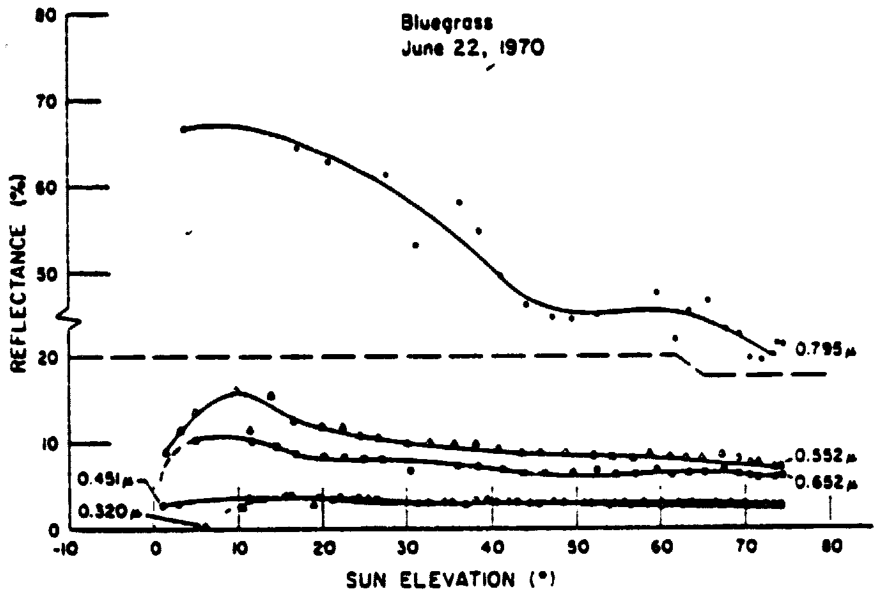

FIG. 14. Hemispheric reflectance of green bluegrass turf at five different wavelengths, as a function of sun elevation.

de Boer, Th. A., N. J. J. Bunnik, H. W. J. van Kasteren, D. Uenk, W. Verhoef, and G. P. de Loor. Investigation into the Spectral Signature of Agricultural Crops During their State of Growth. 1974. Ninth Int. Symp. Rem. Sen Env. University of Michigan. p. 1441-1454.

Field biconical reflectances of mature wheat and cut grass were measured using a spectroradiometer and constant irradiance source. Figures 7 and 8 depict the spectral signatures of what and cut grass, respectively, as a function of wavelength and view angle. In both cases reflectance increased as view angle increased.

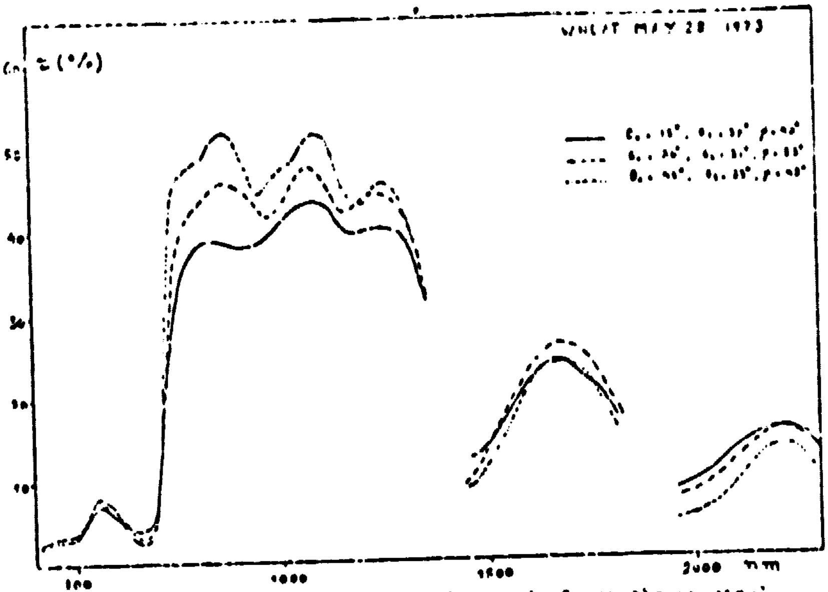

FIGURE 5. Influence of the observation angle θ_0 on the spectral signature of young wheat. Changes by increased observed plant cover are dominant in the chlorophyll absorption region and in the infrared plateau.

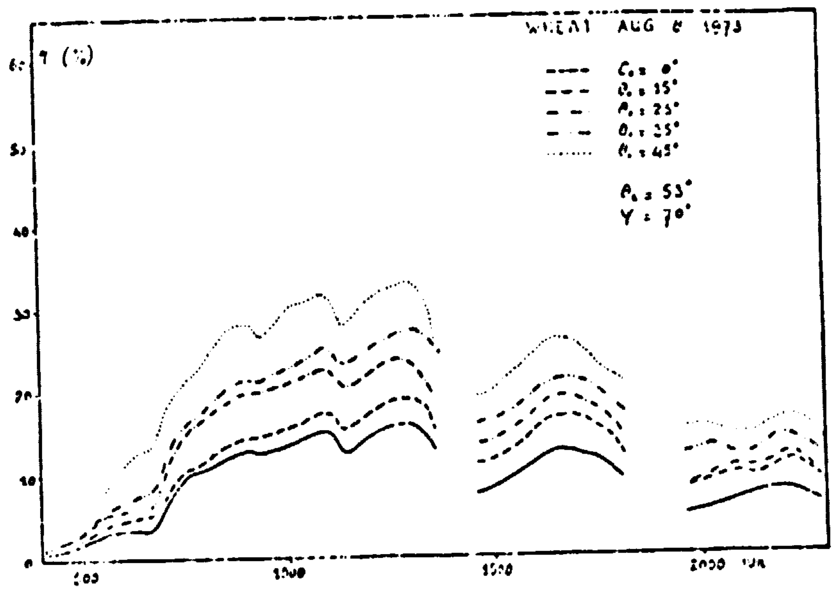

FIGURE 6. Influence of the observation angle θ_0 on the spectral signature of mature wheat. The ground was covered by weeds.

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Duggin, M.J. 1977. Likely Effects of Solar Elevation on the Quantification of Changes in Vegetation with Maturity using Sequential LANDSAT Imagery. Appl. Optics 16:521-523.

Ground based reflectance measurements with the Landsat band passes, wheat reflectances show a general decrease with increasing solar elevation angle (Figure 1). Asymmetry about solar noon is apparently due to differential shadowing caused by row-spacing and orientation. The ratio of MSS band 7 to MSS band 5 resulted in a similar sun angle dependence for all seven varieties of wheat studied. (Figure 2)

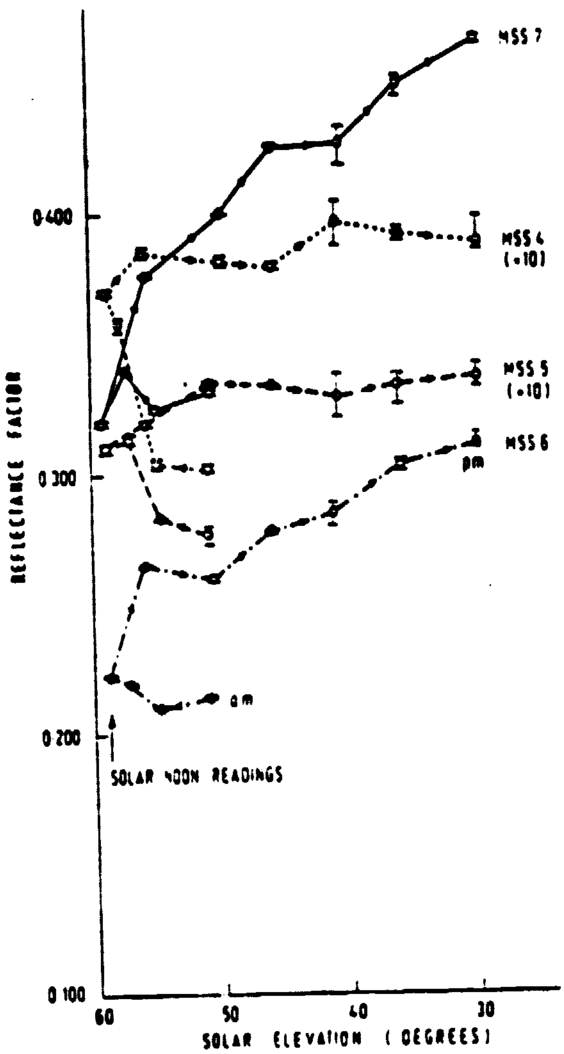

Fig. 1. Reflectance factors of wheat of the Teal variety, measured in the Landsat bandpasses for various solar elevations at Wagga Wagga, Australia, 4 October 1975.

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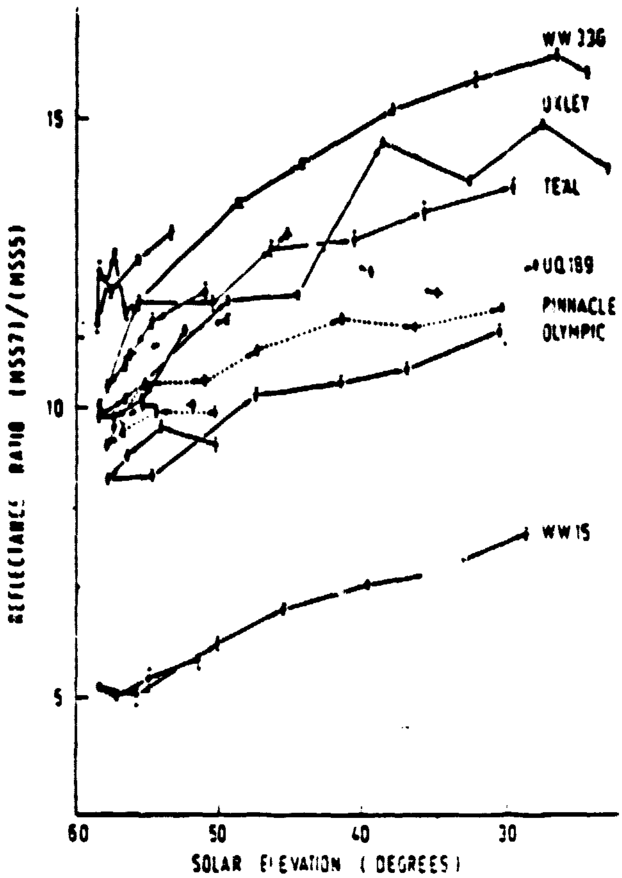

Fig. 3. Reflectance factor ratio MSS 7/5 for seven varieties of wheat for various solar elevations measured at Wagga Wagga, Australia, 4 October 1975.

Egbert, D.D. and F.T. Ulaby. 1972. Effect of Angles on Reflectivity. Photogrammetric Engineering. 38(6):556-564.

Study of reflectance as a function of solar elevation angle, sensor view angle and sensor-sun azimuth angle and wavelength for grass and asphalt. Filtered light meter readings were converted to foot-lamberts and referenced to an Eastman Kodak 18 percent reflectance gray card. Grass reflectance is higher for large view angles. For sun angle of 15° and azimuths of 0° and 180° grass reflectance is five times higher than for 90° azimuth. As sun angle increases beyond 35° reflectance variability decreases and surface approximates a lambertian reflector. Spectrally the curves are similar but those bands that have lower reflectance are less sensitive to extreme angle conditions (Figure 7). Asphalt shows highly specular reflectance at solar angle of 15°, azimuth of 180° and view angle of 80° (Figure 8).

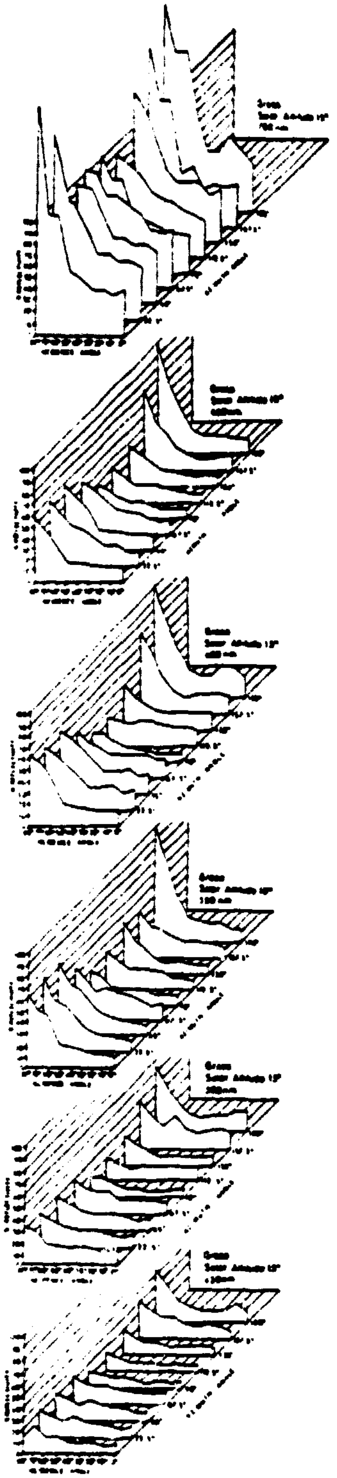

Fig. 7. Angular variation in grass reflectance in specific wavelength bands.

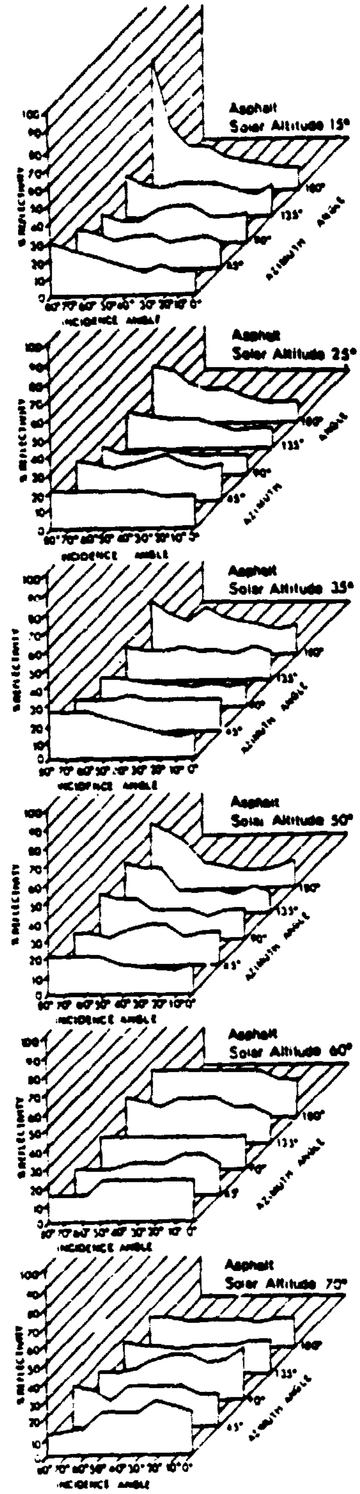

FIG. 8. Angular variation in panchromatic asphalt reflectance at specific solar altitudes.

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Kimes, D. S., J. A. Smith, and K. J. Ranson. 1979. Interpreting Vegetation Reflectance Measurements as a Function of Solar Zenith Angle. NASA Technical Memorandum 80320. Goddard Space Flight Center. Greenbelt, Maryland 20771. 29 p. (Also submitted to Photo. Eng. & Rem. Sens.

Hemispherical conical reflectance of Lodgepole Pine and meadow canopies are plotted for two wavelengths as a function of the solar zenith angle. Arrows indicate the sequence of the data from morning to afternoon. For both canopies, reflectance increased with decreasing zenith angle with the exception of meadow at 0.80 micrometers.

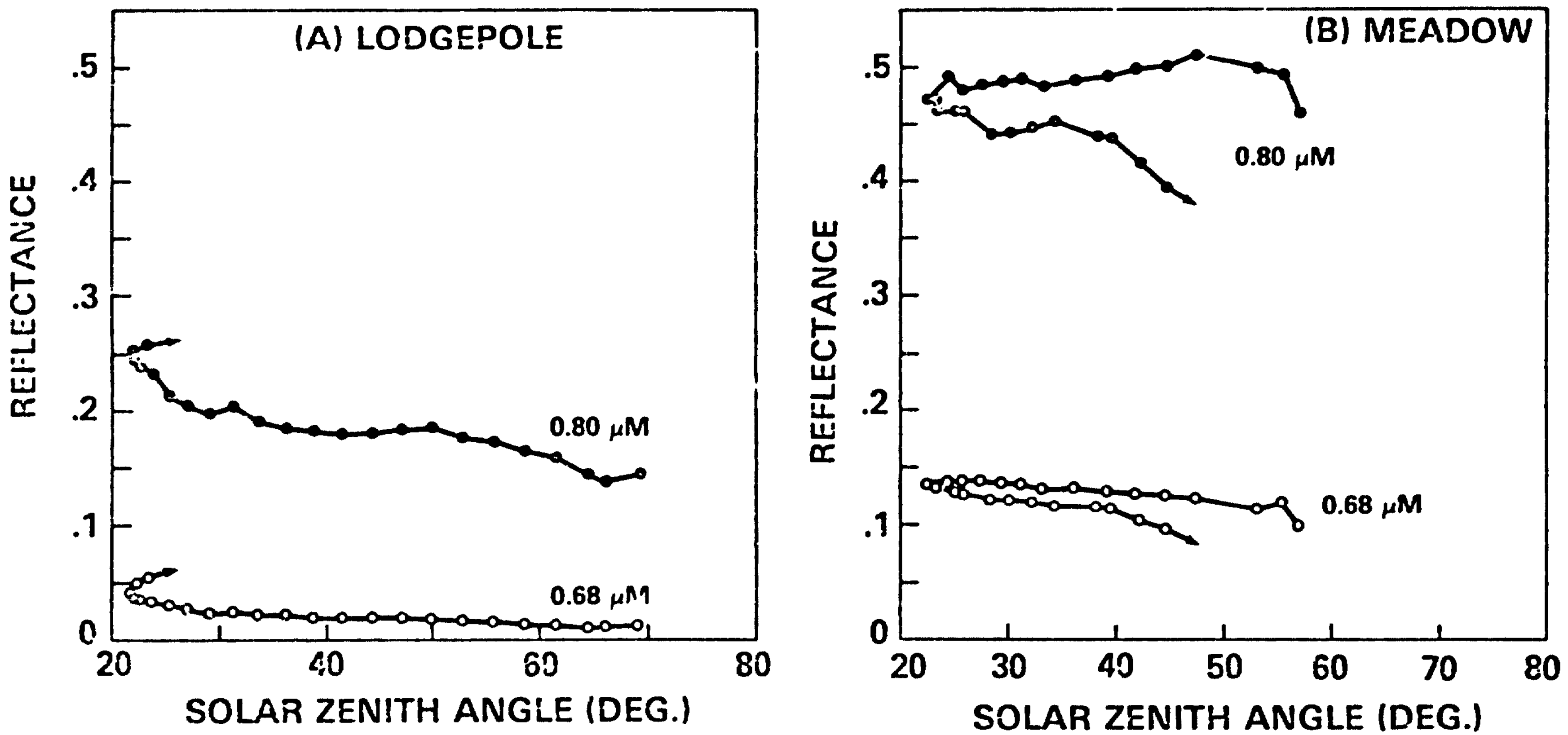

Figure 1. Spectral hemispherical-conical reflectance ρ_λ^C versus solar zenith angle of lodgepole pine (A) and meadow (B) at site 1 for the 0.68 and 0.80 μm bands. Lodgepole and meadow data were collected 0657–1400 hours MDT August 4, 1976 and 0815–1558 hours MDT August 6, 1976.

Kondratiev, K.Y.Z., F. Mironova, and A.N. Otto. 1964. Spectral Albedo of Natural Surfaces. <u>Pure and Appl. Geophysics</u> 59:207-216.

Figure 6 depicts the change in spectral albedo (A) (bihemispherical reflectance) due to sun angle effects for two days. Reflectances can change 30 to 40 percent due to the position of the sun from 26° to 66° for June. For July reflectances change up to 60 percent with a change in the sun angle from 24 to 62°.

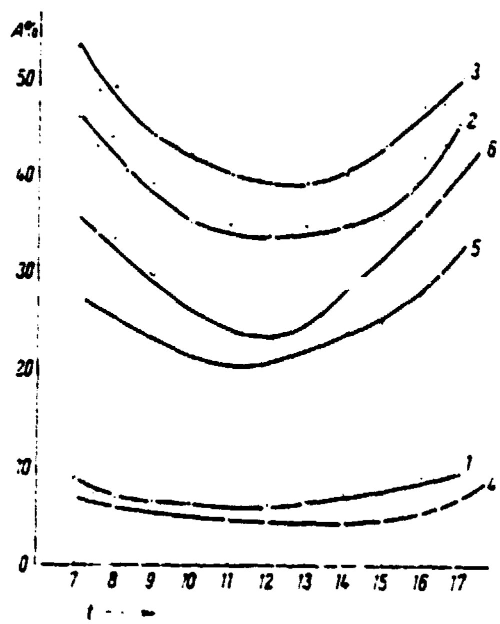

Figure 6

The day course of the spectral albedo of the grass (lucerne)
June: 1 600 mμ, 2 700 mμ, 3 800 mμ; July: 4 600 mμ, 5 700 mμ, 6 800 mμ

Kriebel, K.T. 1978. Average Variability of the Radiation Reflected by Vegetated Surfaces due to Differing Irradiations. Remote Sens. Environ. 7:81-83.

Ranges of biconical reflectances for four natural surfaces given changes in solar zenith angle and optical depth are given as Table 1.

TABLE 1

Percent Change of the Reflected Radiance due to a Change of the Distribution of the Irradiation either by one Degree of the Solar Zenith Angle or by 10% Change of the Optical Depth of the Atmosphere, Averaged over all Directions of Reflection and over all Distributions of the Irradiation.

Surface type	Average change of the reflected radiance: Per degree change of the solar zenith angle	Average change of the reflected radiance: Per 10% change of the optical depth
Savannah	± 1.0%	± 1.6%
Bog	± 0.9%	± 0.7%
Pasture land	± 1.7%	± 1.0%
Conferous forest	± 2.3%	± 1.5%
Average over the four surfaces	± 1.5%	± 1.2%

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Kriebel, K.T. 1978. Measured Spectral Bidirectional Reflection Properties of Four Vegetated Surfaces. <u>Appl. Optics</u> 17(2):253-259.

Biconical reflectances for four natural surfaces in the 521 nm band. Measured radiance referenced to calculated irradiance. Figures 1-4 show increased reflectance for increased view angles. Reflectances at a solar zenith angle of 20° have less azimuthal variation.

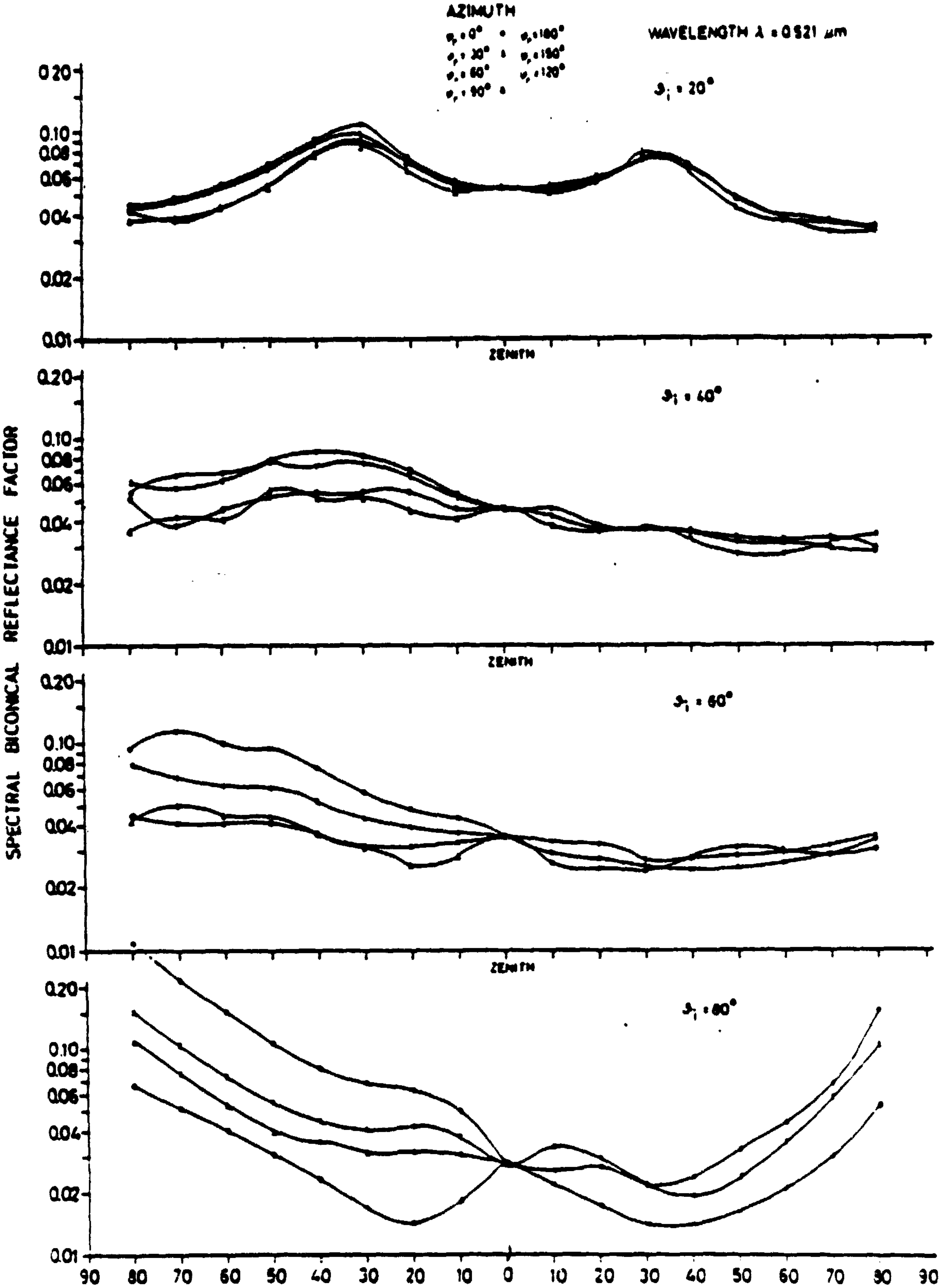

Fig. 1. Spectral biconical reflectance factor for the 0.52-μm wavelength of a savannah vs zenith angle of reflection ϑ_r. The four parts of the figure differ from each other by different zenith angles of the incoming radiation ϑ_i, the curves in each part by different azimuths φ_r.

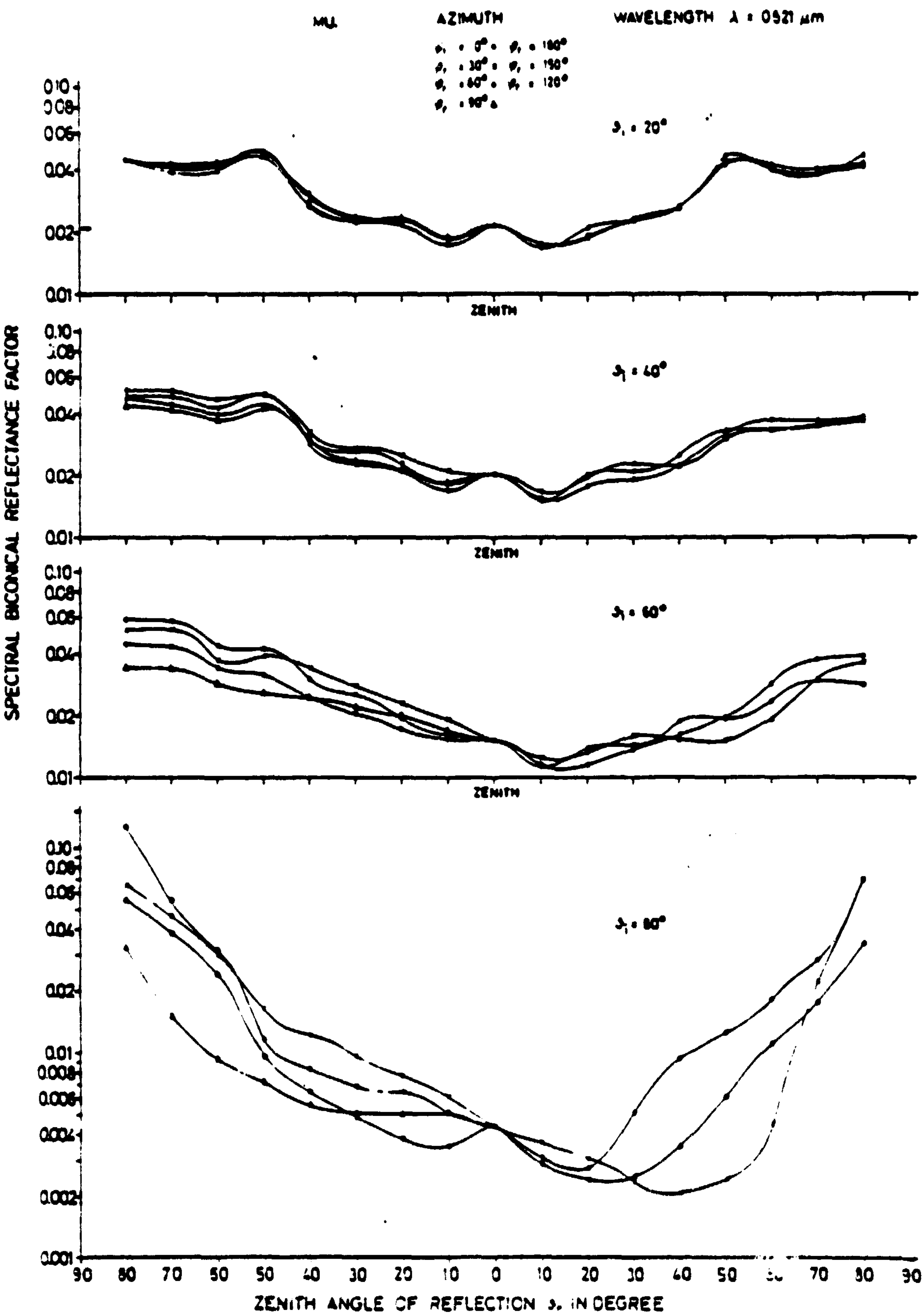

Fig. 2. Same as Fig. 1 but for bog.

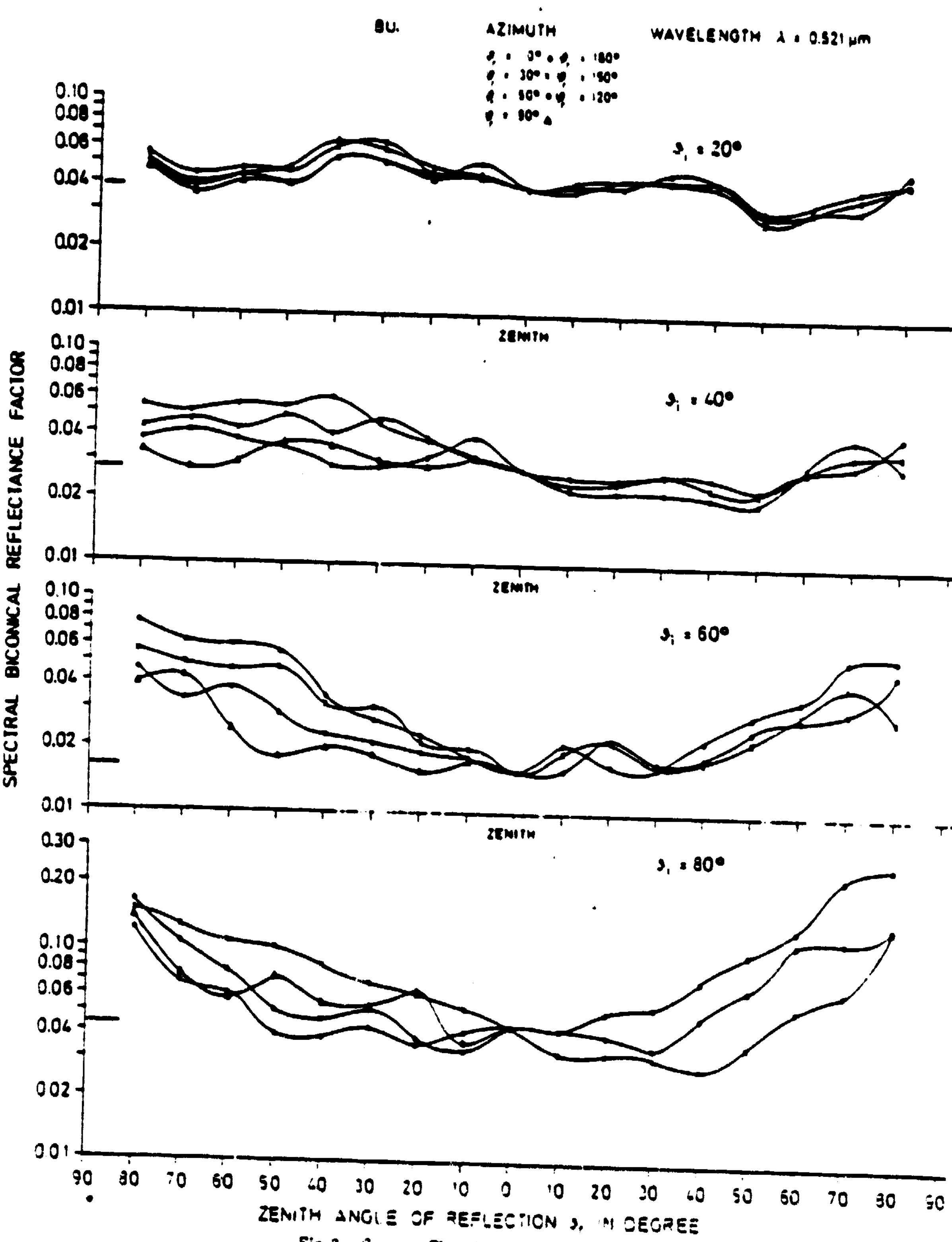

Fig. 3. Same as Fig. 1 but for pasture land.

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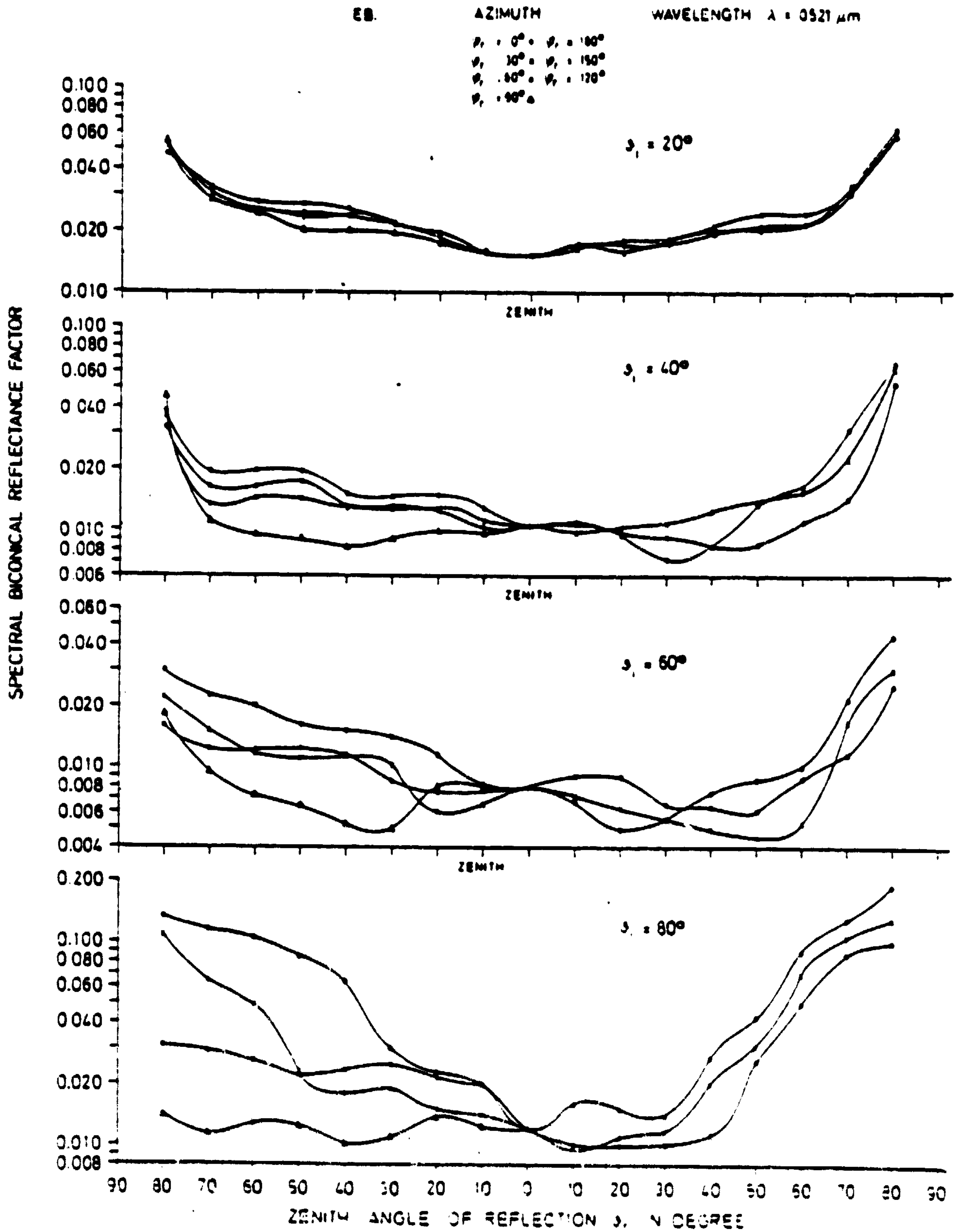

Fig. 4. Same as Fig. 1 but for coniferous forest.

Rao, V.R., E.J. Brach, and A.R. Mack. 1979. Bidirectional Reflectance of Crops and the Soil Contribution. Remote Sens. Environ. 8:115-125.

Compares reflectances of several crops at low oblique-viewing angles and varying solar zenith and azimuth angles. Normalized bi-conical reflectances are calculated from $\rho = \pi(I(\lambda)/E)$ with E computed as a function solar geometry and atmospheric parameters.

The effects of varying sun and sensor view angle and sun-sensor azimuths produce larger reflectance differences at higher sun angles between 750 and 1800 nm. All sensor-sun combinations show strong absorption in 1350 nm water absorption band.

Notation: Ψ = sun-sensor azimuth angle, $\emptyset$ = view or scattering angle (Figure 2).

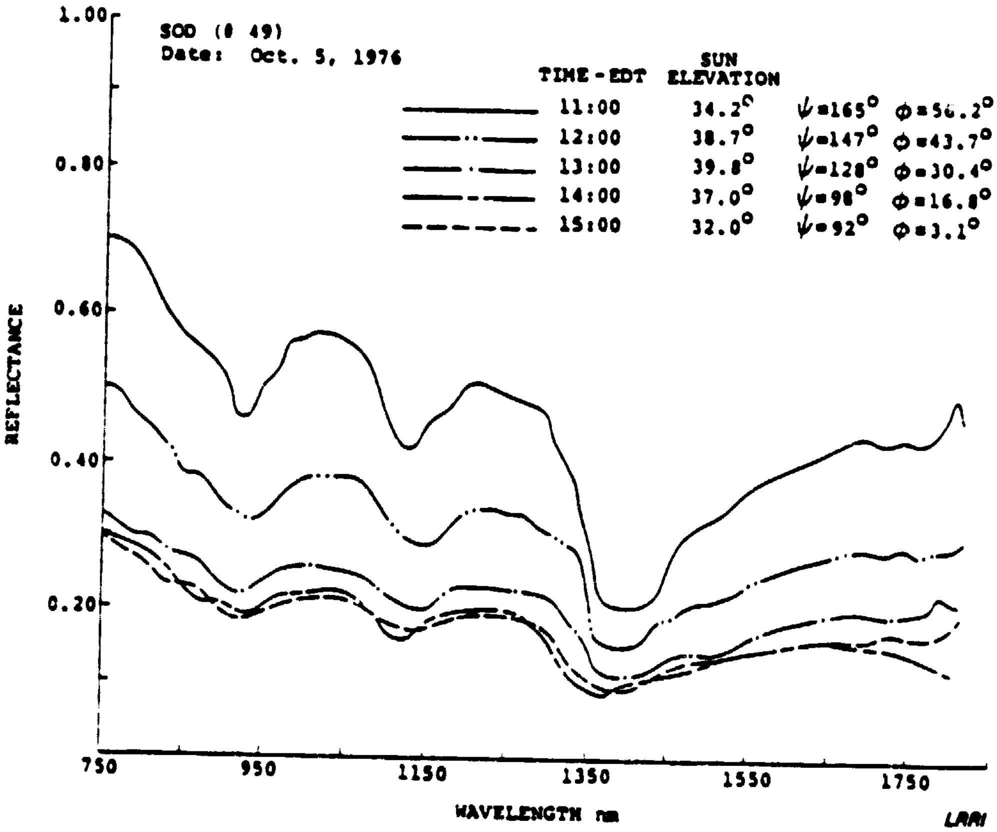

FIGURE 2

Salomonson, V.V. and W.E. Marlatt. 1971. Airborne Measurements of Reflected Solar Radiation. Remote Sens. Environ. 2:1-8.

Table II describes the variations in directional reflectance observed over desert lake bed, grassland and vegetation-swamp. Columns 5 and 7 list directional reflectances for narrow and broad band passes, respectively. Columns 6 and 8 give the ratios of directional reflectance for narrow and broad band passes, respectively, and the average value of bidirectional reflectance. The results in Column 10 (Column 5 - Column 7) demonstrate, primarily, the effect that spectral reflectance of the surface has on the relative magnitude of the directional reflectances observed for the two band passes. Adjusted directional reflectances in Column 9 show that the desert lake has the highest broad band reflectance and densely vegetated surface has the lowest. Directional reflectance increases with increasing solar zenith angle for all three surfaces.

TABLE II

Directional Reflectances and Relative Anisotropy Observed by the Nimbus Medium Resolution Radiometer over Different Surfaces at Different Solar Zenith Angles

(1) Flight No.	(2) Surface	(3) Solar zenith angle (°)	(4) Incoming energy (S') (Ly/min)	(5) $(r_D)_N$	(6) $(r_D)_N/\bar{r}_0$	(7) $(r_D)_B$	(8) $(r_D)_B/\bar{r}_0$	(9) $\frac{S}{S'}(r_D)_B$	(10) $(r_D)_N-(r_D)_B$
1	Desert lake bed	58–59	0.72	0.28	1.13	0.23	1.14	0.33	0.05
2	Desert lake bed	70–73	0.35	0.24	1.23	0.19	1.18	0.34	0.05
3	Grassland	59–63	—	0.19	1.29	C.19	1.30	—	0.00
4	Grassland	57–59	—	0.21	1.31	0.19	1.28	—	0.02
5	Grassland	55–57	—	0.18	1.26	0.19	1.18	—	−0.01
6	Grassland	66–69	0.57	0.23	1.27	0.24	1.30	0.32	−0.01
7	Grassland	59–62	0.72	0.22	1.22	0.22	1.18	0.30	−0.00
8	Grassland	78–82	—	0.13	2.18	0.16	1.80	—	−0.03
9	Vegetation-swamp	56–61	0.74	0.07	1.68	0.11	1.37	0.16	−0.04
10	Vegetation-swamp	70–73	0.40	0.08	2.45	0.11	1.61	0.18	−0.03

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B. Phase Angle Effects on Polarization

(See also Coulson et al,1965)

Egan, W.G., J. Grusauskas, and H.B. Hallock. 1968. Optical Depolarization Properties of Surfaces Illuminated by Coherent Light. Appl. Optics 7(8):1529-1534.

Depolarization measurements with 632.8 nm laser radiation were made of mineral and vegetation samples. At higher phase angles (angle between source and sensor) wet soil samples of sand, gravel and silt depolarize 632.8 nm light less than dry samples. Fresh samples of rhododendron and holly leaves and pine needles are clearly differentiated by depolarization at 0° viewing angle but less so at 60° viewing angle. Drying of the leaves generally increases polarization, as was the case with soil samples (Figure 6). Depolarization differences change with viewing angle due to shadowing and leaf geometry. Soil particle size and porosity also affect the depolarization characteristics (Figures 3 and 4).

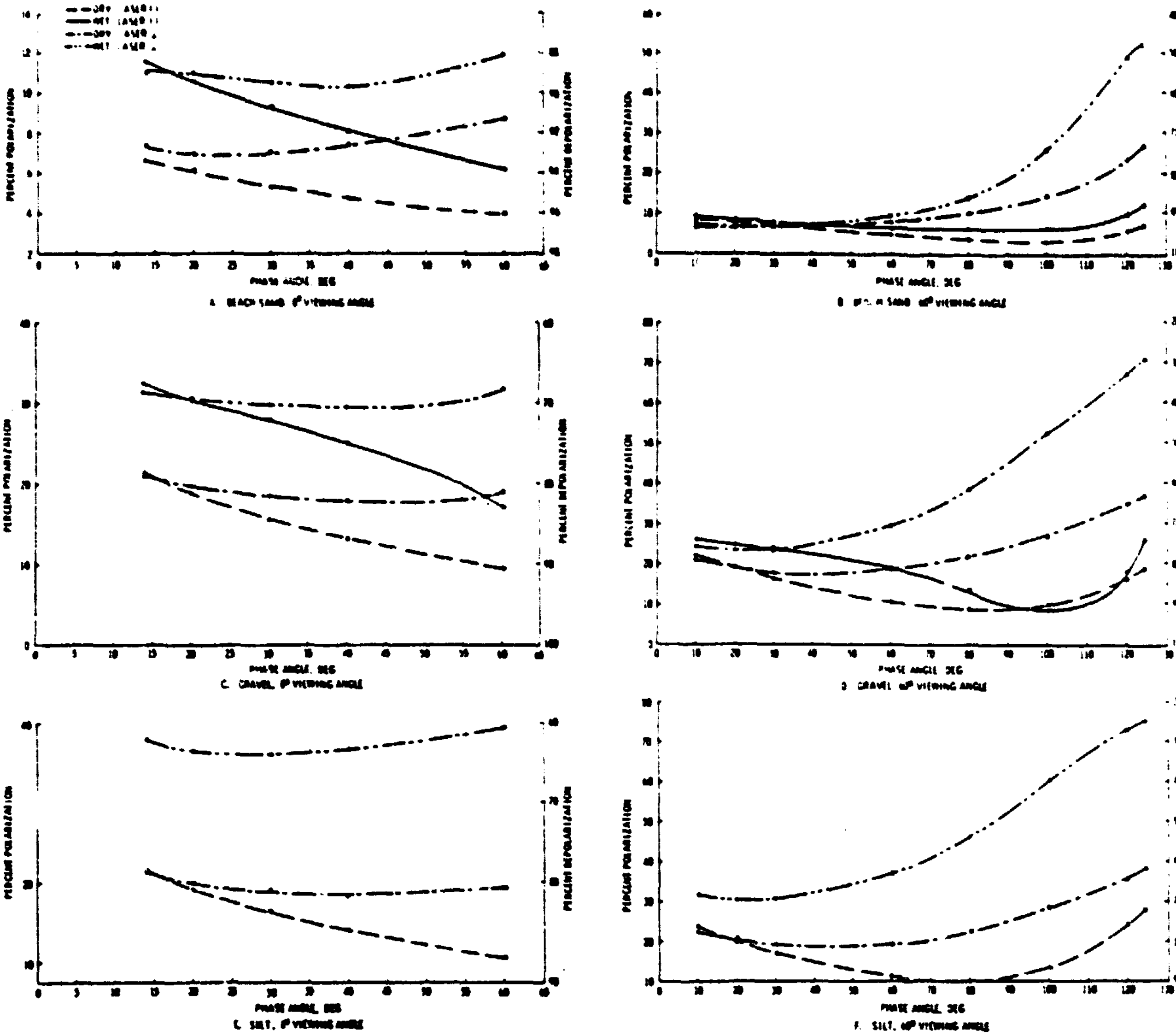

Fig. 5. Effect of moisture on depolarization of various soils (beach sand, gravel, silt): (A) beach sand, 0° viewing angle; (B) beach sand, 60° viewing angle; (C) gravel, 0° viewing angle; (D) gravel, 60° viewing angle; (E) silt, 0° viewing angle; (F) silt, 60° viewing angle.

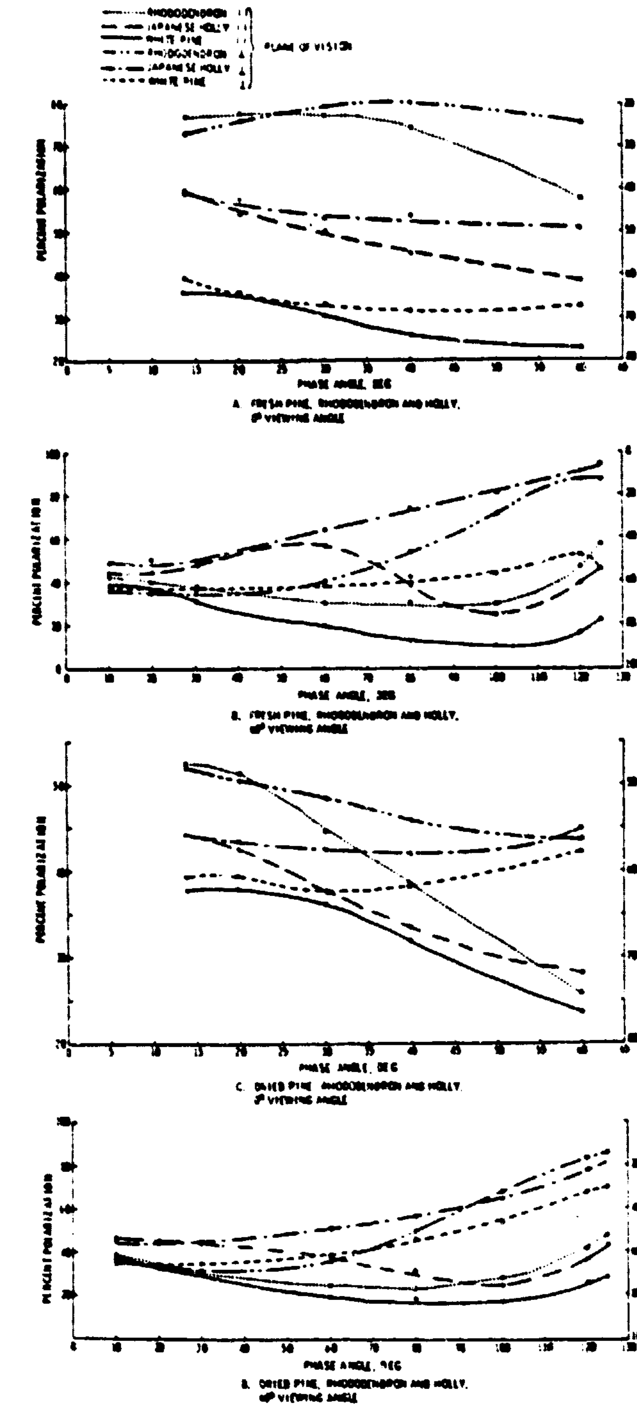

Fig. 6. Depolarization by evergreen leaves; effect of drying: (A) fresh pine, rhododendron, and holly, 0° viewing angle; (B) fresh pine, rhododendron, and holly, 60° viewing angle; (C) dried pine, rhododendron, and holly, 0° viewing angle; (D) dried pine, rhododendron, and holly, 60° viewing angle.

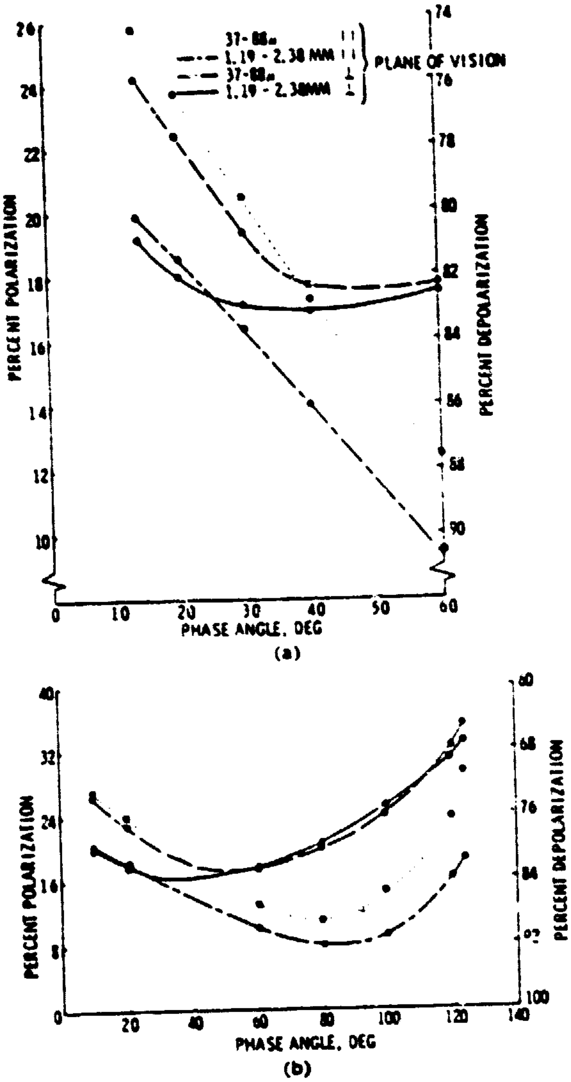

Fig. 3. Limonite (Venango County, Pa.): effect of particle size on depolarization (37–88 μ, 1.19–2.38 mm): (a) 0° viewing angle, (b) 60° viewing angle.

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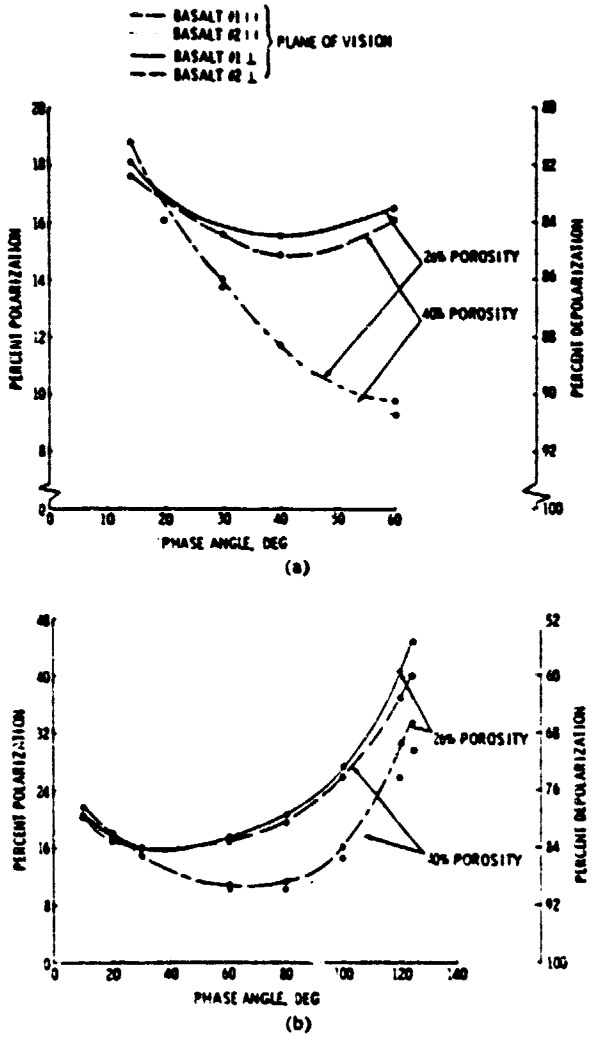

Fig. 4. Basalt (Chimney Rock, N.J.): effect of surface porosity on depolarization: (a) 0° viewing angle, (b) 60° viewing angle.

Egan, W.G. 1970. Optical Stokes Parameters for Farm Crop Identification. <u>Remote Sens. Environ</u>. 1:165-180.

Measurements of first and second Stokes parameters were made of several farm crops. Figures 5 a-b and 6 a-b show the relative brightness obtained in the first and second Stokes parameters, respectively, for alfalfa and potato leaves. The second Stokes parameter may be better than the first for identifying species and soil moisture differences.

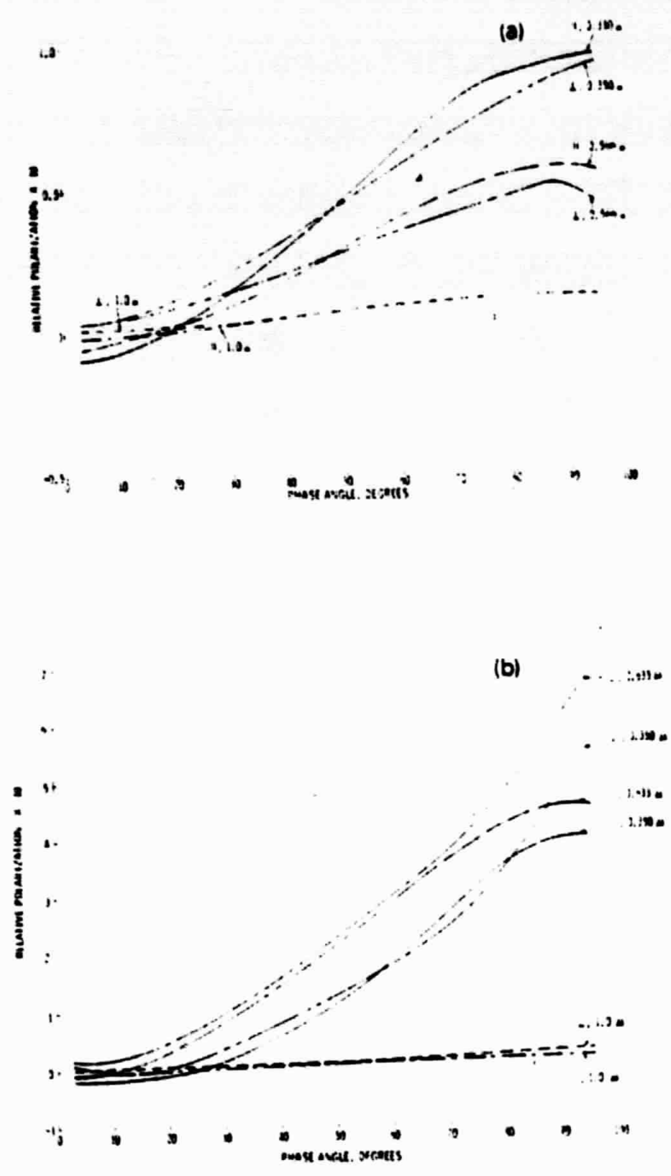

Fig. 6. Spectropolarimetric curves for 30° incidence angle (second Stokes parameter). (a) Alfalfa leaves. (b) Long Island potato leaves

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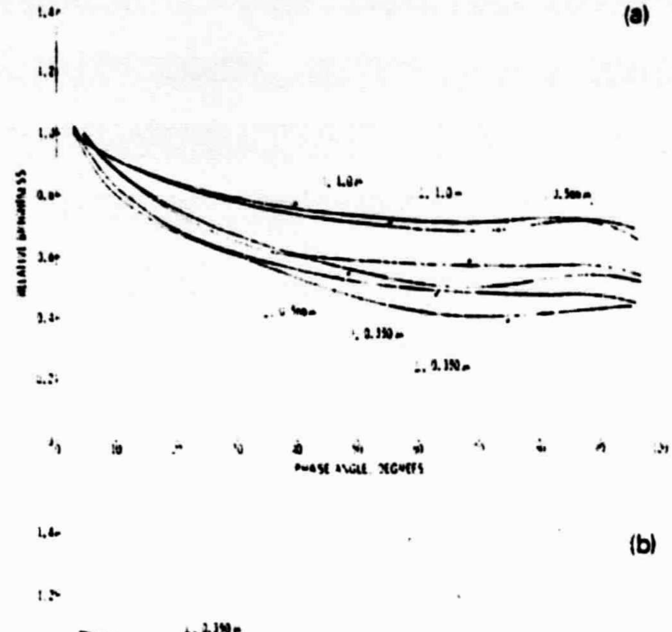


Fig. 5. Spectrophotometric curves for 30° incidence angle (first Stokes parameter). (a) Alfalfa leaves. (b) Long Island potato leaves.

C. Applications of Ratio Techniques

(See also Duggin,1977)

Kanemasu, E.T. 1974. Seasonal Canopy Reflectance Patterns of Wheat, Sorghum, and Soybean. Remote Sens. Environ. 3:43-47.

Ratioing the bihemispherical reflectance of agricultural crops in the 545 nm and 645 nm wavelength bands indicate very little change due to solar elevation angle variation. Near IR reflectance decreased with increased solar elevation angle for wheat and sorghum.

Soybean near IR reflectances varied due apparently to changes in leaf angle with sun elevation (Figure 3).

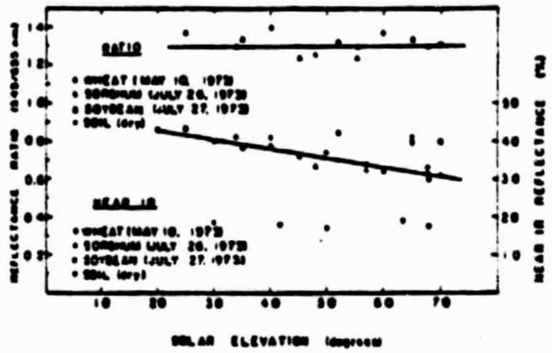
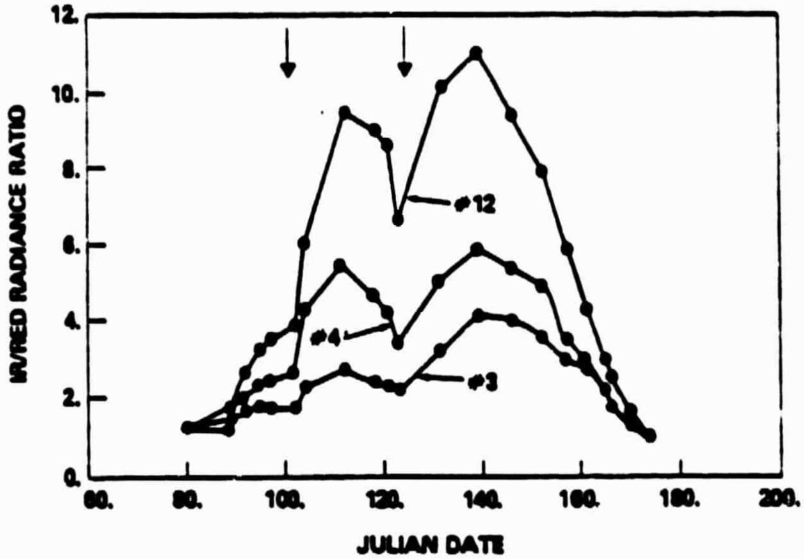


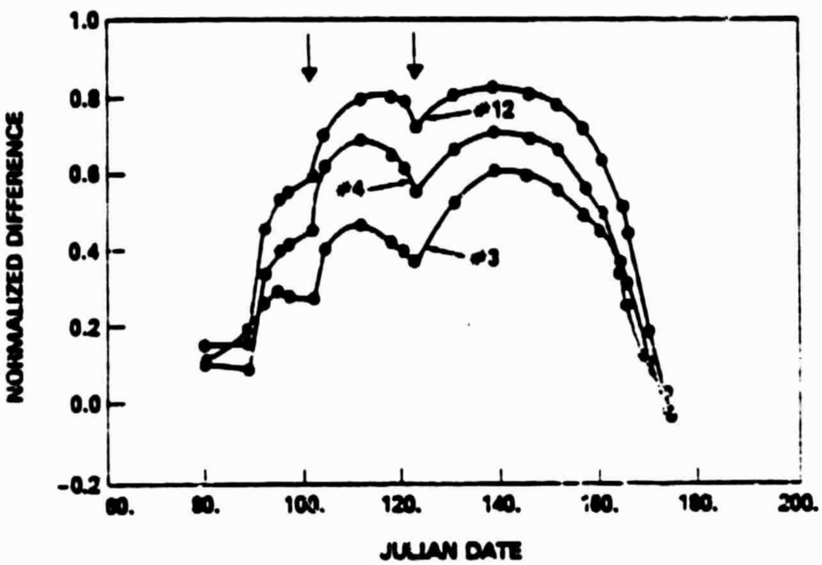
FIG. 3. Effect of solar elevation (0-horizon) on the reflectance ratio of 545—655-nm waveband and on the near-infrared reflectance (750 nm) of wheat (boot stage), sorghum (early heading), soybean (late podding), and dry silty clay loam.

Tucker, C.J., B.N. Holben, J.H. Elgin, Jr., and J.E. McMertrey, III.
1979. The Relationship of Red and Photographic Infrared Spectral Data to Grain Yield Variation Within a Winter Wheat Field. NASA Technical Memorandum 80318, NASA/Goddard Space Flight Center, Greenbelt, Maryland. 22 p.
(Also submitted to Photog. Eng. & Rem. Sens.)

Infrared to red narrow band radiance ratios of winter wheat were acquired throughout a growing season. IR/red radiances plotted against Julian date show the effects of canopy development and reaction to water stress and recovery for three sample plots. The normalized difference (ND) (IR-red)/(IR+red) shows similar results.



(A)



(B)

Figure 2. The ir/red radiance ratio (A) and the normalized difference (B) from three 2- x 3-in plots plotted against Julian data. The vertical arrows represent episodes of rainfall. Note the response of the two spectral variables to the occurrence of precipitation which ended periods of water stress.

D. Angular Considerations for Enhancing Classification

Bunnik, N.J.J. 1978. The Multispectral Reflectance of Shortwave Radiation by Agricultural Crops in Relation with their Morphological and Optical Properties. Wageningen. Mededelingen Landbouwhogeschool. Nederland 78-1. 175 p.

Bunnick describes the effects of source and sensor geometry on canopy reflectance. The following observations were made:

1) At a 75° zenith view angle background soil reflectance in the visible wavelengths may be neglected for most crops.

2) Measurements where the source and sensor angles are equivalent (canopy hot spot) the relationships between spectral reflectance and canopy variables such as leaf color and status could be detected. An active conical scanning system is recommended.

3) Detection normal to the earth's surface or under a zenith angle of 51.8° eliminates the influence of canopy leaf angle distribution on reflectance as a function of the apparent soil cover percentage.

4) Various combinations of reflectance values in the green, red and near IR produce a well defined relation with soil cover, LAI and differences in soil moisture content. The ratio of reflectance in the red and green bands for view angles coincident with source angle and 51.8° is independent of canopy structure.

5) Active conical scanning under an angle of 51.8° using an aircraft platform allows for the collection of reflectance data under cloudy skies with less effect from atmospheric variability.

Malila, W. A., R. H. Hieber, and J. E. Sarno. 1974. Analysis of Multispectral Signatures and Investigation of Multi-Aspect Remote Sensing Techniques.

A theoretical calculation of the equivalent Lambertian reflectance to be expected from a leafless forest superimposed on a snow-covered background. Reflectance versus bark reflectance is calculated for several cases of stand density and branching volume. Results for 0 degrees and 45 degrees off-nadir are shown.

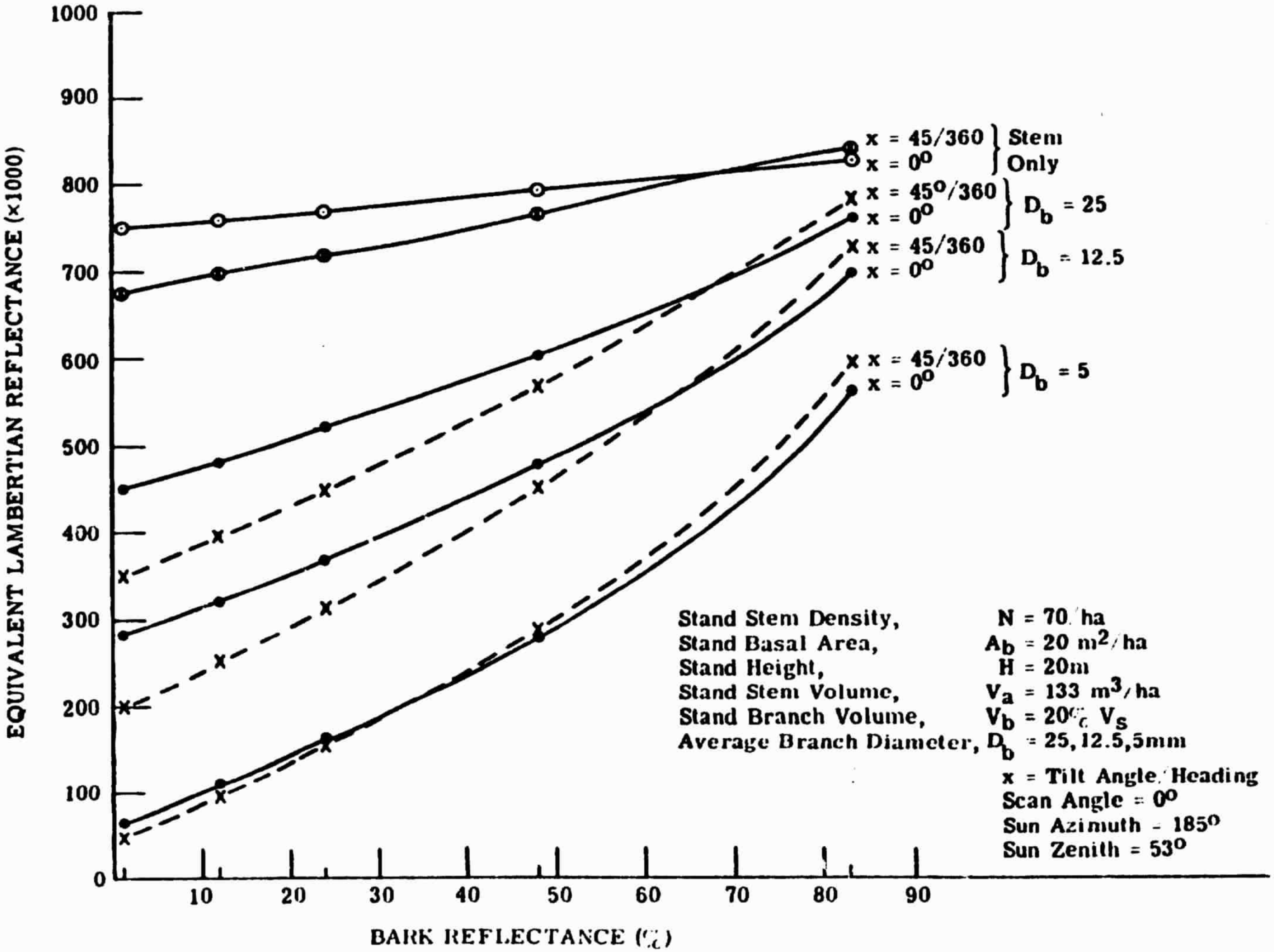


FIGURE 26. EFFECT OF BRANCHES ON THEORETICAL MULTI-ASPECT REFLECTANCE FOR LEAFLESS FOREST

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C-3

FORMERLY WILLOW RUN LABORATORIES, THE UNIVERSITY OF MICHIGAN

Oliver, R.E. and J.A. Smith. 1974. A Stochastic Canopy Model of Diurnal Reflectance. Final Report. U.S. Army Research Office Durham. DAHC04 74 G0001. 82 p.

Vegetation canopy structure in terms of the mean projection of leaf elements is least sensitive to leaf angle distribution when viewed at an inclination angle of 57.5° (Figure 5). Apparent directional reflectance (hemispherical-directional) as a function of zenith view angle for five canopy geometries is also insensitive at the 57.5° view angle (Figure 11). The effects of leaf area index on canopy reflectance are shown in Figure 12. These results indicate that discrimination of LAI should be maximized at larger view angles.

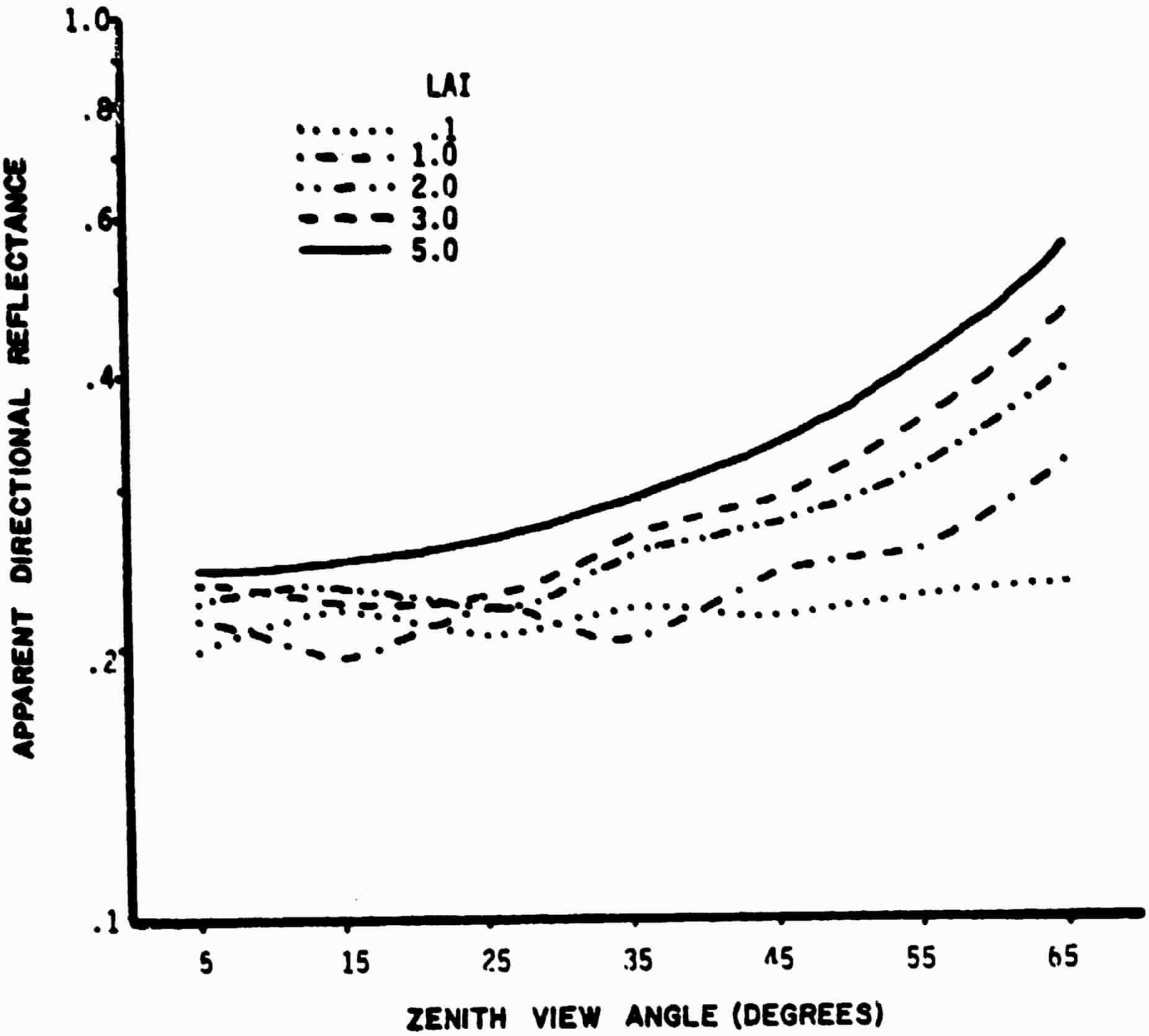

Figure 12. Effect of Vegetation Leaf Area Index on Canopy Apparent Directional Reflectance. The results shown represent the simulation of a Spherical canopy at a wavelength of .8μm and a solar zenith of 37°.

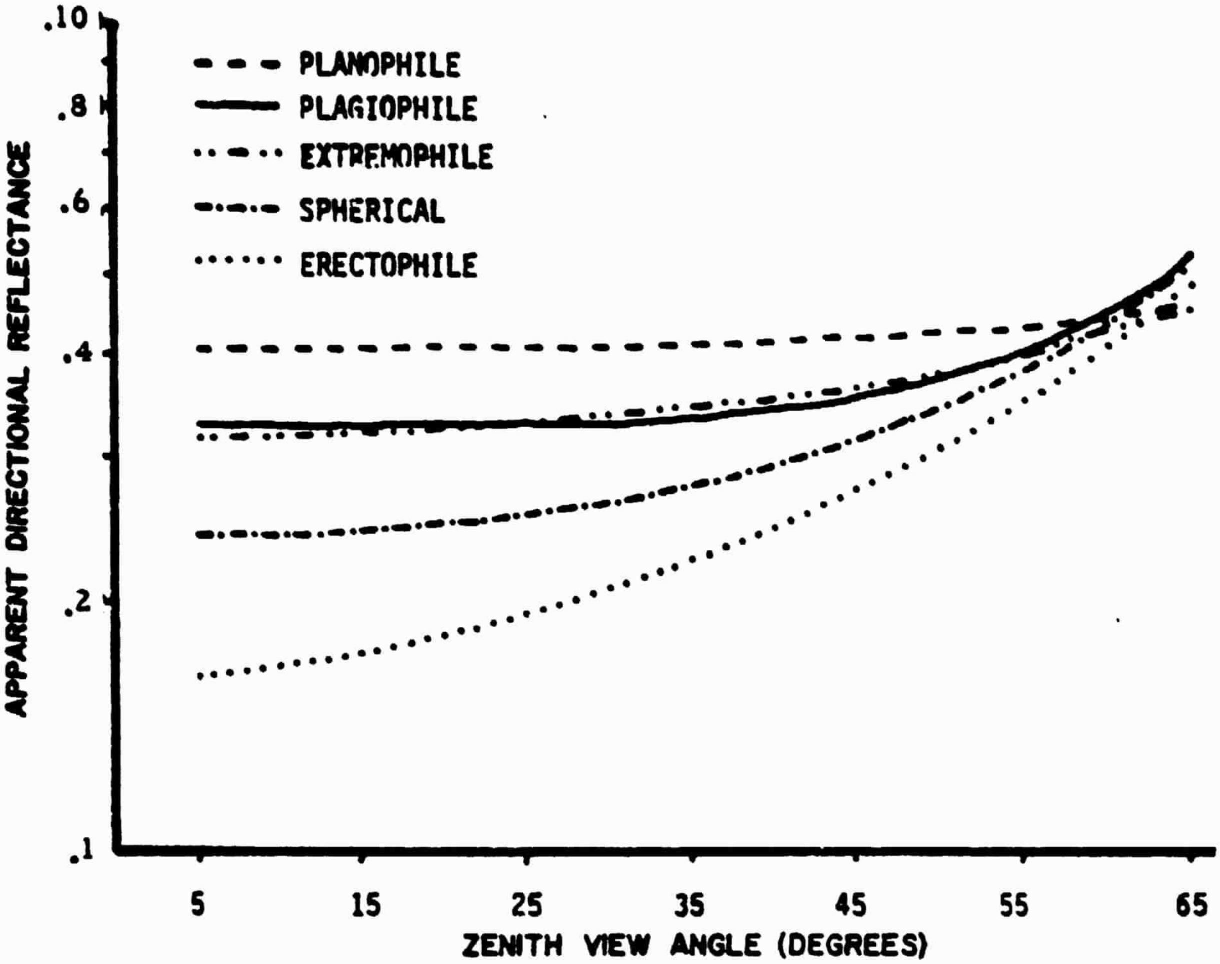

Figure 11. Predicted Apparent Directional Reflectance for the Canopy Types Shown in Figure 4.

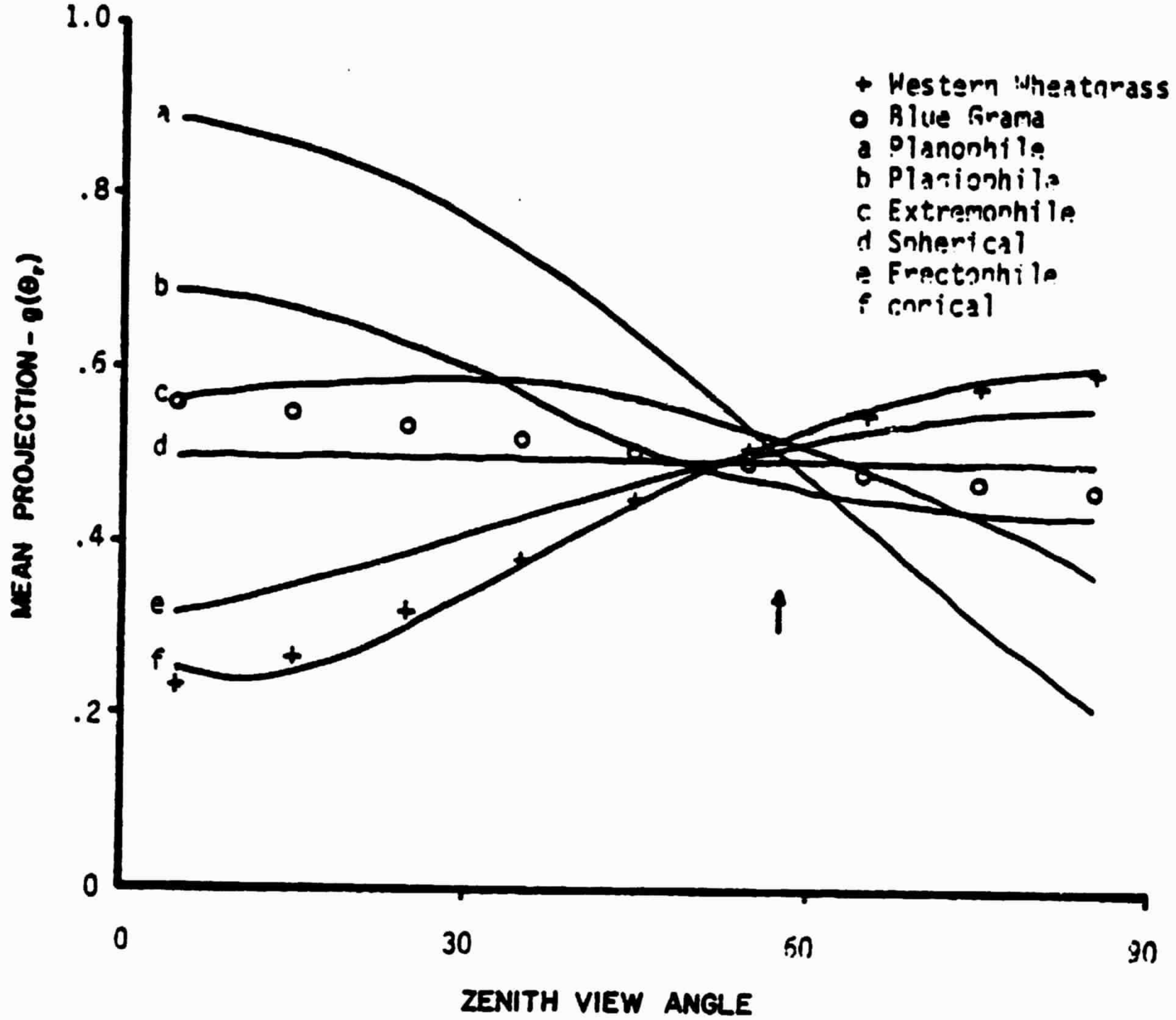

Figure 5. Mean Projection of a Leaf Element for Each of the Canopy Types Shown in Figure 4.

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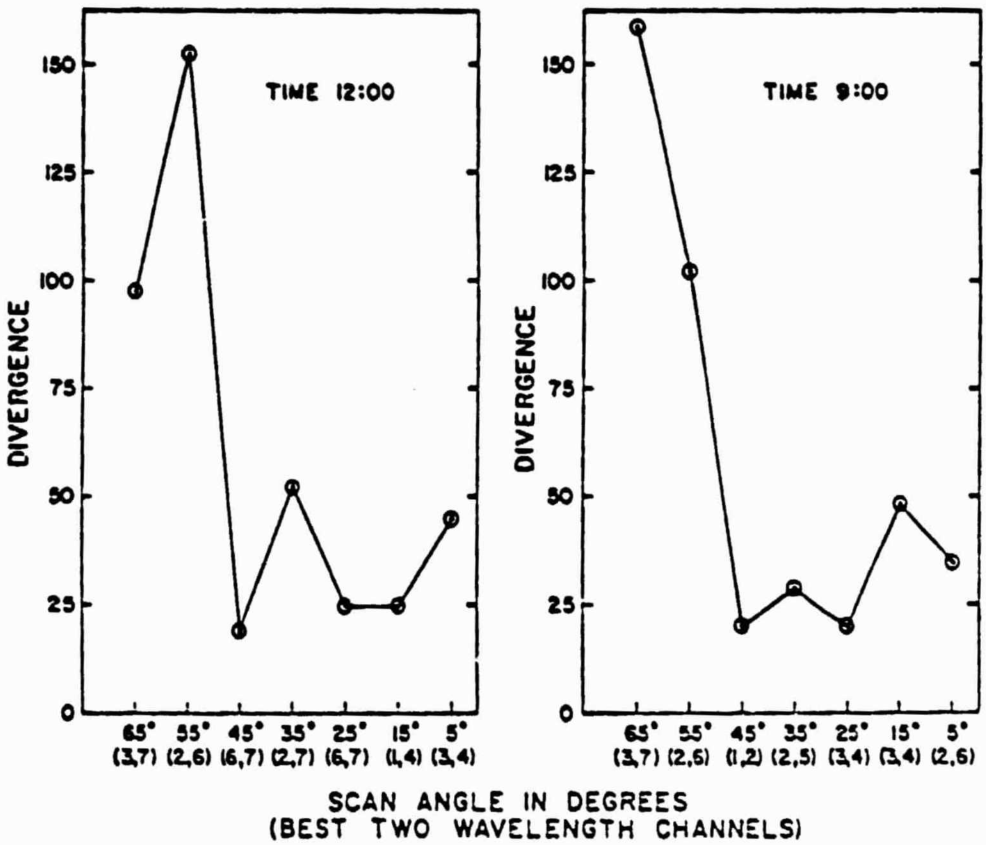
Smith, J. A. and R. E. Oliver. 1974. Effects of Changing Canopy Directional Reflectance on Feature Selection. App. Opt. 13 (7): 1599-1604.

A Monte Carlo Canopy reflectance model was utilized to predict the bidirectional reflectance distribution function for two Bouteloua gracilis canopies differing only in leaf-area-index. The apparent directional reflectance was calculated for two solar zenith angles (22 and 44 degrees) as a function of wavelength. Separability, as measured by the divergence criteria, was calculated as a function of look angle. Maximum discrimination is predicted for large zenith look angles near 55 degrees.

CHANGES IN FEATURE SELECTION



Variation in maximum divergence with scan angle and best two wavelengths out of seven. Results are given for 12:00 (solar zenith angle 22.3 degrees) and 9:00 (solar zenith angle 44.5 degrees) computer simulations.